The Benefits of Global Landmarks for Spatial Learning under Stress

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ABSTRACT

In a fast-paced digital society, individuals increasingly rely on computerized location-based services to efficiently find their way through unfamiliar environments. However, scientific evidence is increasingly showing that despite digital navigation assistance helping people to find their way, it can cause wayfinders to become "mindless" of the traversed environment, thus acquiring no or very little spatial knowledge in the long term. It is still not entirely clear what causes these impairments or how the design of navigation devices can be improved to counteract such undesirable effects. The objective of this thesis is to gain empirical insights into the role of stressful navigation conditions for potential spatial learning impairments, and to identify the features in the environment for which it is particularly important that wayfinders' pay attention to and thus increase their spatial knowledge even when experiencing stress. Building on existing work in spatial cognition, cognitive geography, and stress research, the studies of this thesis investigate whether and how highly visible landmarks can improve memory of large spaces like cities, and how that may be influenced by navigators' stress states.

It is widely accepted that landmarks serve a key role for the development of spatial knowledge, and there has been increasing interest in integrating landmarks into automated navigation instructions in recent decades. Specifically, recent studies have pointed to a potential advantage of so-called global landmarks that are visible from several locations in an environment for spatial orientation and route learning. However, there has been little research on the difference in mentally encoding and learning the locations of global landmarks as compared to landmarks that are only visible locally. In this thesis, I conducted two virtual reality experiments that assessed human participants' capability to acquire spatial knowledge from local or global landmark configurations in situations with and without stress. Insights from this work can help designers of future navigation systems, and industry decision makers, to reconsider which and when landmarks should be presented in navigation systems. For example, future navigation assistance may dynamically adapt the display of local and global landmarks according to the contextual demands of the wayfinder.

In Study I, I investigated the role of time pressure in learning the spatial relations among local landmarks (e.g., a shop along the route) as compared to global landmarks (e.g., a tower in the distance) during navigation through virtual cities. During this navigation, participants used a navigation aid and had explicit learning

instructions for the different local or global landmark configurations. Participants' performance in a survey knowledge test after navigation suggests that global landmark configurations were not represented more accurately than local landmark configurations, and that survey knowledge acquisition was not impaired under time pressure. In contrast to prior findings, the results of Study I indicate no advantage of distant global landmarks for spatial knowledge acquisition.

In Study II, I investigated the role of working memory in acquiring survey knowledge from sequentially (locally) or simultaneously (globally) visible landmark configurations during navigation through virtual cities. As in Study I, participants navigated routes through virtual cities, but both local and global landmarks were located along these routes. Moreover, one group of participants performed a concurrent spatial task that aimed to interfere with the active processing of information in working memory. I expected that an increase in spatial working memory demands would impair survey knowledge for sequentially visible local landmarks more than for simultaneously visible global landmarks. I also assessed individuals' working memory capacity, because I expected greater capacity to be beneficial for the sequential integration of local landmarks over time. My findings show a negative effect of concurrent task demands for both local and global landmark learning. Furthermore, the data indicates that participants had improved spatial knowledge of globally visible landmarks as compared to locally visible landmarks along the route. Finally, Study II revealed that individual working memory capacity moderates the accuracy of acquiring spatial knowledge of global landmarks. Only participants with greater working memory capacity are able to benefit from globally visible landmarks.

In summary, this work has identified a number of cognitive and contextual conditions that impair users' ability to take advantage of globally visible landmarks for spatial learning. Based on these conditions, the present work provides design guidelines for future learning-aware navigation systems. For example, my analysis of participants' learning performance indicates that users with greater working memory capacities have the necessary cognitive resources available to take advantage of global landmarks for spatial learning. While this might imply that the navigation systems of tomorrow need to be aware of users' spatial abilities to optimize information display, future research should also identify means to support navigators with low working memory capacity.

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ACRONYMS

WM Working Memory

SSQ Simulator Sickness Questionnaire

SSSQ Short Stress State Questionnaire

EDA Electro Dermal Activity

NS-SCR Nonspecific skin conductance response

SCL Skin Conductance Level

Chapter 1

INTRODUCTION

Imagine you are on your way to a job interview. You leave the train and in front of you lies an unfamiliar city. Unfortunately, the power supply of your navigation device is running low and will probably run out soon. You think that it would be embarrassing to arrive late to the job interview if the device failed. In such situations, you might experience an acute stress response, negative emotions, intense body reactions, and intrusive thoughts with respect to being late for appointments (Zimring, 1981) or getting lost in the city (Bronzaft, Dobrow, & O'Hanlon, 1976; Lawton, 1994). Facing the potential failure of your device, you realize that you might need to find the way back to the train station without the support of your navigation device. To which aspects of the environment should you attend to easily orient yourself?

The study of navigation and spatial cognition in cognitive geography sheds light on such questions and the manner in which people acquire spatial knowledge in different contexts (Montello, 2015). Spatial knowledge describes people's beliefs and understanding regarding their spatial surroundings. For the hunter-gatherers, accurate spatial knowledge was essential, for example to remember the paths to the edible plants, or to safely return after capturing a prey. Today, accurate spatial knowledge is important because it increases peoples' freedom to move when technology is unavailable or malfunctioning. For example, a navigation support device might have outdated geographical data, weak satellite reception, or empty batteries. In such cases, spatial knowledge of an environment will increase the efficiency and confidence with which you find your way. Furthermore, in an urbanized world, spatial knowledge allows people to adapt their navigation behavior to changing city infrastructure (e.g., temporarily blocked routes) or inappropriate route instructions (e.g., impassable terrain or unpleasant districts). Beside these rather rare scenarios, imagine the advantages of a system that supports your acquisition of spatial knowledge so that you are later able to navigate your surroundings without the device.

1.1 MOTIVATION AND PROBLEM STATEMENT

There is increasing evidence that using navigation support devices can cause users to be "mindless" of the environment and acquire no or very little spatial understanding of the environment (Parush, Ahuvia, & Erev, 2007; Axon, Speake, & Crawford, 2012; Burnett & Lee, 2005; Aslan, Schwalm, Baus, Krüger, & Schwartz, 2006; Huang, Schmidt, & Gartner, 2012). It is not entirely clear what causes these impairments, and prior research proposed several possible mechanisms (Willis, Hölscher, Wilbertz, & Li, 2009). There is some agreement that a lack of active encoding of the spatial surroundings is the core of the problem (Willis et al., 2009; Girardin & Blat, 2010; Leshed, Velden, Rieger, Kot, & Sengers, 2008; Patrick Péruch & Wilson, 2004). The acquisition of spatial knowledge may also depend on which aspects of the environment are being attended (Gardony, Brunyé, Mahoney, & Taylor, 2011; Shelton & Gabrieli, 2004; Montello, Waller, Hegarty, & Richardson, 2004). To address these issues, recent research has investigated ways to improve the design of navigation interfaces such as features that engage users with their environment (Parush et al., 2007; Brügger, Richter, & Fabrikant, 2019), but the environmental aspects that should be emphasized by navigation interfaces for supporting spatial learning are still unclear.

In addition, stress may occur during navigation, for example if we cannot find our destination, struggle with traffic and crowded environments, or act under time pressure. In such situations, we may experience stress because we are traveling through dynamic and cognitively demanding environments (Matthews, Szalma, Panganiban, Neubauer, & Warm, 2013). For example, we often need to rush to an appointment while attending to other pedestrians, adhering to traffic rules, and monitoring physical obstacles to avoid collisions. We may be mentally overloaded by performing different concurrent tasks such as navigating and using our hand-held device to write messages or receive phone calls. Previous research also demonstrates the importance of emotionally arousing experiences and acute stress states for cognition, attention, working memory, and long-term memory (Lazarus & Folkman, 1984; Lupien, Maheu, Tu, Fiocco, & Schramek, 2007). Similarly, stress and other emotional states affect the capabilities of navigators to mentally process spatial information and acquire spatial knowledge (Duncko, Cornwell, Cui, Merikangas, & Grillon, 2007; Evans, Skorpanich, Gärling, Bryant, & Bresolin, 1984; Richardson & Tomasulo, 2011; Gardony et al., 2011).

With this background in mind, to which aspects of an environment should navigation interfaces guide attention to support spatial learning in general and in stressful navigation scenarios? The present thesis addresses the question by comparing the difficulty of learning local and global landmark configurations in stressful and non-stressful navigation scenarios. I will present empirical evidence for these types of landmarks and to which extent they support the accurate and efficient formation of spatial knowledge.

1.1.1 Research gap

Prior research has shown that landmarks support orientation and the formation of abstract mental representations from vast amount of available spatial details (Evans et al., 1984; Couclelis, Golledge, Gale, & Tobler, 1987; Sadalla, Burroughs, & Staplin, 1980; Presson & Montello, 1988; Golledge, 1999; Sorrows & Hirtle, 1999). Landmarks are features of the environment that can be easily recognized. For example, a remarkable statue located at a city square can serve as a mental anchor that supports encoding, representation, and recall for other spatial locations in that environment (Sadalla et al., 1980). Due to their key role for understanding and memorizing space (Siegel & White, 1975; Foo, Warren, Duchon, & Tarr, 2005; Richter & Winter, 2014; Steck & Mallot, 2000), there has been much interest in the benefits of integrating landmarks into navigation support systems for giving route directions (Raubal & Winter, 2002, e.g.,) and spatial learning (e.g., Schwering, Krukar, Li, Anacta, & Fuest, 2017). Empirical evidence on landmarks and spatial learning indicate that route knowledge can improve as a result of attention towards visually salient landmarks (Sorrows & Hirtle, 1999) that are located along the route (Lovelace, Hegarty, & Montello, 1999) or at decision points (Jansen-Osmann & Berendt, 2002; Denis, Pazzaglia, Cornoldi, & Bertolo, 1999). Route knowledge describes knowledge of the sequence of landmarks and related actions (e.g., turning left) and is important for retracing routes or finding one's way back along a previously traveled route.

Prior research has also indicated that landmarks that are visible from several locations in a large area may improve spatial orientation in familiar environments and memory acquisition of routes(Steck & Mallot, 2000; Wenig et al., 2017; Schwering et al., 2017; R. Li, Korda, Radtke, & Schwering, 2014). However, evidence is less clear about the benefits of attending to global landmarks for the formation of survey knowledge in unfamiliar environments (H. Li, Corey, Giudice, & Giudice, 2016; Meilinger, Schulte-Pelkum, Frankenstein, Berger, & Bülthoff, 2015; Castelli, Latini Corazzini, & Geminiani, 2008). Survey knowledge has been defined as memory for the relative directions and distances of objects and routes in an environment (Siegel & White, 1975) and is often considered to allow navigators to dynamically plan routes or shortcut between familiar places. So far, a clear advantage of globally visible objects has only been confirmed for small-scale spaces or objects depicted on 2D screens (Ruotolo, Ruggiero, Vinciguerra, & Iachini, 2012; Meilinger, Strickrodt, & Bülthoff, 2016; Lecerf & De Ribaupierre, 2005; Blalock & Clegg, 2010; Lupo et al., 2018). Regarding the navigation of large-scale spaces, there have been no controlled studies which compare the benefits of globally visible landmarks in the distance, to globally visible landmarks along the route. Furthermore, local and global landmark learning has not yet been investigated during highly demanding tasks such as navigation under time pressure. In the majority of studies on local and global landmarks, participants were able to allocate attention towards spatial learning nearly undisturbed (H. Li et al., 2016; Castelli et al., 2008; Ruotolo et al., 2012; Meilinger, Strickrodt, & Bülthoff, 2016). Indeed, only one study has addressed the role of stress on acquiring spatial knowledge from local or global landmarks (Gardony et al., 2011). In the present dissertation, I argue that this is a critical shortcoming of the literature because everyday navigation often happens under time pressure and within a highly dynamic and cognitively demanding setting. The motivation of the present research is thus to study the differences of using local or global landmarks for survey knowledge acquisition, however, to also account for contextual factors, including time pressure, physiological stress, and cognitive load.

1.2 RESEARCH QUESTIONS

The main goal of the present thesis is to elucidate the difficulty of acquiring survey knowledge from local and global landmark configurations in situations with and without stress. To examine the difficulty of local and global landmarks for learning, I observed spatial learning performance for situations in which working memory should function better or worse. Participants learned landmark configurations under low/high psychophysiological stress or with-/without concurrent task demands. The "learning difficulty" of a set of landmarks is then defined using the accuracy of participants' survey knowledge when acquired under these contextual demands that limited participants' attentional processing. By this definition, a set of landmarks that result in more accurate memory under high working memory demands should be less difficult than a set of landmarks that results in less accurate memory in similar circumstances. Spatial learning performance may also rely on the cognitive capacities of the users (Wolbers & Hegarty, 2010), especially under stress or high task load. Therefore, the present study considers spatial abilities as an important moderator for the learning of local and global landmarks during assisted navigation. With this particular motivation in mind, I defined the following research questions:

1. How accurate is the acquisition of survey knowledge from local and global landmarks?

2. How do contextual stressors interfere with successful survey knowledge acquisition of local and global landmarks?

3. What is the role of individuals' spatial abilities during spatial knowledge acquisition for local and global landmark configurations, and how do spatial abilities interact with survey knowledge acquisition under stress?

1.3 CONTRIBUTIONS

The objective of the present research is to contribute to scientific knowledge in cognitive geography by providing insights into the manner humans encode and mentally represent large-scale urban environments. By focusing on the role of specific environmental aspects (i.e., landmark types), the present dissertation extends the early work in environmental cognition that was conducted by urban planners (Appleyard & Lintell, 1972; Lynch, 1960) and geographers (Downs & Stea, 1973). This area of research emphasized the role of physical settings for human behavior and spatial memory (Evans et al., 1984) before wayfinding was associated so strongly to digital support systems. The significance of the environmental structure for spatial memory formation was recently also supported by evidence in spatial cognition research that demonstrated the important role of the environmental structure for reference frame selection (Mou & McNamara, 2002; Shelton & McNamara, 2001). Finally, the results will complement recent studies in spatial cognition on survey knowledge acquisition for landmarks in large-scale environments (Richter & Winter, 2014; Castelli et al., 2008) while accounting for individual differences in cognitive abilities.

The second intended contribution of the present dissertation is to elucidate the roles of emotions and pyschophysiological stress responses in spatial learning. With the assessment of individuals' emotions (Matthews et al., 2013) and underlying psychophysiological responses to stressors (Russell & Barrett, 1999). I aim to identify potential interactions between the learning of local and global landmarks and psychophysiological states. Such interactions may indicate the possible limitations of memory for local and/or global landmark configurations when users are stressed or their cognitive capacity is limited by external task demands.

The third objective is to contribute to the design of navigation applications by providing practical recommendations. When should a navigation device guide attention to which kind of landmarks for the support of survey knowledge acquisition. These insights aim to serve practitioners, such as the designers of future navigation systems, and industry decision makers. The successful design of landmark-based navigation support systems can be achieved only if landmark selection and display matches the perceptual and cognitive capabilities of the users. The findings of the present research can contribute to this goal by suggesting which type of landmarks should be highlighted in order to support survey knowledge acquisition and how this benefit might be constrained by task conditions such as time pressure and external workload. Given recent technological advances in sensor technology and real-time data accessibility, future navigation systems may be able to respond in real-time to different conditions by adapting their displays and guiding attention towards particular features.

1.4 RELEVANCE

But, why bother about spatial knowledge when omnipresent navigation technologies provide us with the information we need to travel? The ability to orient from memory has some important benefits for humans. Spatial knowledge can empower people to reach destinations autonomously without relying on access to navigation technology. For example, a person who acquired spatial knowledge of an environment is more likely to find his way through that environment in case satellite reception is weak, the batteries run out, or the navigation system malfunctions in some other way.

Furthermore, spatial knowledge can enable users to assess the quality of the automatically generated directions provided to them. Users with spatial knowledge can recognize failures in navigation systems and devise alternative routes. This may be helpful when the route directions provided by a navigation system are inaccurate or undesirable because of temporarily blocked routes (e.g., by construction sites), impassable terrain, or unpleasant districts. In some popular and terrifying incidents, imprecise system data caused ambulance drivers to take several wrong turns during emergencies and to fail to save human lives (Irvine, 2009). In these particular cases, spatial knowledge could have helped the drivers to recognize incorrect directions. The colloquial phrase "death by GPS" refers to the most extreme examples of users that followed the incorrect directions of a device and consequently lost their life by, for example, starving in the desert (Knudson, 2011; McKenzie, 2016; Milner, 2016).

Finally, users with spatial knowledge can focus on other tasks besides navigation and may not be distracted from mentally processing navigation instructions. The mental processing of instructions during assisted navigation forces users to divide their attention between the device and the environment (Gardony, Brunyé, Mahoney, & Taylor, 2013). Navigating from memory relieves users from these negative cognitive consequences of divided attention. Spatial memory may be particularly crucial during car navigation because attention is required for driving and monitoring traffic (e.g., other cars and pedestrians).

1.5 THESIS APPROACH

The present thesis applies hypothesis-driven psychological research methods to investigate the questions defined above. Specifically, two navigation studies in the laboratory targeted these identified research gaps. In these studies, individuals' followed routes in large-scale virtual environments and were then tested on their spatial knowledge of these environments. The use of virtual reality facilitated the manipulation of environmental variables, experimental control, and the determination of cause-and-effect relations. For example, the visual appearance of the to-be-learned landmarks could be carefully operationalized according to the needs of the defined research questions. Furthermore, the use of virtual reality allowed us to exclude most factors that could potentially interfere with our measures and were not of interest, such as car traffic, pedestrians, weather conditions, and prior knowledge of the environment (Meilinger, Riecke, & Bülthoff, 2014; Shelton & Gabrieli, 2004; Richardson, Montello, & Hegarty, 1999). One limitation of virtual environments is providing the multi-sensory cues that are typical during real-world navigation. Therefore, the results of this thesis are restricted to knowledge regarding visual processing of the environment. However, there is much empirical evidence that the spatial cognition of sighted individuals strongly relies on visual perception (Cattaneo et al., 2008) and that visual cues alone may be sufficient for updating spatial positions and orientations (e.g., Riecke, Cunningham, & Bülthoff, 2007; Kearns, Warren, Duchon, & Tarr, 2002). Still, due to the lack of coherent multi-sensory cues, virtual reality systems can cause simulator sickness symptoms in users and impair their orientation ability. To account for these influences, this empirical work will observe participants' symptoms and include them in the analysis.

Following recent literature from spatial cognition, navigation, and behavioral geography, I developed a theoretical framework that models the cause-and-effects structure of my variables of interest (see Figure 1) and used this model throughout the research process to generate research questions and hypotheses. This framework relates geographical, task, and user factors with the core cognitive mechanisms underlying spatial information processing, such as attention, working memory, and survey knowledge. The boxes denote the variables of interest that will be studied in the present thesis. The labels outside the boxes describe to which group of factors the variable belongs. For example, the variable working memory capacity is a trait factor that is assumed to be a constant within an individual, where arousal and distress are state factors that may change with the situation and within a person. The labeled arrows denote the relationships between the variables with the direction of the arrow indicating the direction of the effect (causality). For example, in the present framework, distress is assumed to impair working memory but not the other way around. Of course, there might be influences between the variables that are not considered in the present model, because these influences are assumed to be marginal or of no primary interest in the present research project.

Due to the limitations of virtual reality for providing multi-sensory cues, the proposed framework aims to uniquely account for spatial knowledge acquisition during visual navigation. Working memory occupies a central part of this framework because evidence supports the notion that working memory is strongly involved in the construction of spatial knowledge derived from visual input during navigation (Meilinger, Knauff, & Bülthoff, 2008; Wen, Ishikawa, & Sato, 2011, 2013; Gras, Gyselinck, Perrussel, Orriols, & Piolino, 2013; Labate, Pazzaglia, & Hegarty, 2014). Working memory can be considered a temporal buffer (Humphreys, Lynch, Revelle, & Hall, 1983; Baddeley, 2000) that streamlines the processing of material received from the environment (e.g. landmarks). For the construction of survey knowledge in long-term memory, navigators have to store different pieces of spatial information over time and transform these pieces so that they can be integrated into a common representation (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006). Consistent with previous studies that demonstrated individual differences in spatial learning performance after learning in large-scale environments (Hegarty et al., 2006; Ishikawa & Montello, 2006; Weisberg, Schinazi, Newcombe, Shipley, & Epstein, 2014), the present framework considers individuals' spatial abilities to help explain previously observed relations between working memory capacity and spatial learning (G. L. Allen, Kirasic, Dobson, Long, & Beck, 1996), as well as between working memory and stress (Sandi, 2013). Importantly, the present framework aims to describe these particular factors and their effects on the construction of survey knowledge during navigation, but is not intended to explain other types of navigation scenarios, such as memory consolidation during navigation in familiar environments or the recall of spatial knowledge during stressful navigation episodes.

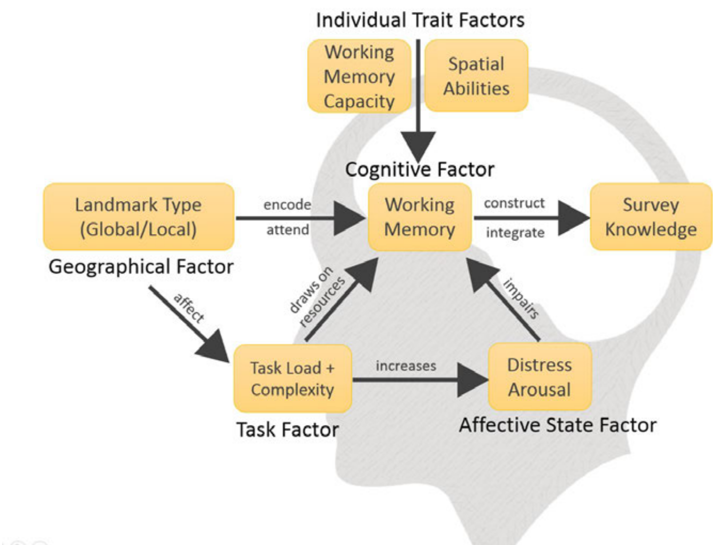


Figure 1: Factors of interest which are influencing survey knowledge acquisition during ground level movement.

1.6 OVERVIEW

The thesis is structured as follows:

In Chapter 1, we have identified three core questions, including the benefits of globally visible landmarks for spatial learning, the impact of psychophysiological stress on survey knowledge acquisition, and the role of individual differences in spatial abilities for learning local and global landmarks. Taken together, these questions are motivated by the objective to improve navigation systems for spatial learning.

Chapter 2 presents scientific research in geography and spatial cognition on the process of spatial knowledge acquisition during navigation through large-scale environments. First, I define navigation and wayfinding and summarize the debate on the development of spatial mental representations during navigation. Then, I focus on literature that indicated that mentally encoding spatial information of different scales affect the manner in which different working memory subsystems (and individual differences in working memory) moderate learning efficiency for local and global landmarks. Finally, I summarize prior literature that examined the influence of psychophysiological stress states on working memory and spatial knowledge acquisition during navigation.

Chapter 3 provides an overview of the environments, experimental variables, and measures that have been used for data collection and analysis for both studies. At this chapter's core, I describe how theoretical concepts were translated into measurable variables. Given that both studies of the present thesis employed virtual reality, the chapter also introduces relevant findings from the literature that address the use of virtual reality for studying human navigation.

Chapter 4 reports the specific objectives, methods, and results of Study I. In this study, I examined whether survey knowledge acquisition during a stressful task (i.e., navigating under time pressure) is more accurate for local landmarks along the route or global landmarks in the distance. This study was the first navigation study to compare the accuracy of survey knowledge towards multiple global landmarks to the accuracy of survey knowledge towards multiple local landmarks.

Chapter 5 reports the objectives, methods, and results of Study II. In this study, I investigated whether survey knowledge acquisition is affected by a spatial concurrent task (i.e., spatial tapping task) and if learning is more accurate for local or global landmark configurations when they are both located along the route. An additional goal of Study II was to examine the role of working memory for processing and acquiring knowledge of local and global landmark configurations. These findings revealed important differences in local and global landmark memory and relate these differences to individual differences.

Chapter 6 provides the analyses of two questions. First, was there a relation between participants simulator sickness and their stress experience in the present thesis? Second, does the stress data that was collected throughout the studies (i.e., physiological arousal or self-reported stress states) provide a better model for explaining peoples' spatial knowledge acquisition than our experimental manipulations? Using a statistical model comparison approach, I could show that self-reported data increases explanatory power over the experimental manipulations.

Chapter 7 reviews and critically discusses the thesis results. Examining the results of both studies, this chapter reveals that global landmarks are only helpful for spatial learning under certain conditions.

Chapter 8 summarizes the empirical work of the field including the thesis' contribution. Furthermore, it translates the findings into design recommendations that can be easily employed by developers of future navigation devices.

Chapter 2

RELATED WORK

2.1 SPATIAL LEARNING

The study of spatial learning is concerned with the process of acquiring and maintaining spatial information in memory from seconds to many years (Ishikawa, 2018). Most researchers describe spatial knowledge as mental spatial representations and thus assume a representational theory of mind according to which individuals construct mental models to mediate their interaction with the world (Thagard, 2005). In the scientific literature, there is little doubt that humans have the ability to construct mental spatial representations that are often called spatial knowledge or "the cognitive map" (O'keefe & Nadel, 1978). Most of the strongly debated questions regarding mental spatial representations relates to the qualities or format of these representations (e.g., topological or metric relations) and how these change with increasing experience in an environment (Chrastil & Warren, 2014; Montello, 1998; Stankiewicz & Kalia, 2007). One fundamental distinction in memory systems during learning relates to the duration of the encoded memories. While some types of information only need to be remembered for immediate use (short-term-memory), other types of information must be stored (almost) permanently (long-term-memory). To understand the format of mental representations in long-term memory and their development, we first need to understand how humans acquire and temporarily maintain spatial information during navigation.

2.1.1 Navigation

To remain oriented and reach destinations efficiently, humans have sophisticated spatial skills. The term "navigation" subsumes a set of these skills that, according to Montello (2005), is goal-directed travel through the environment. Montello (2005) divides navigation into two distinct processes named locomotion and wayfinding. Locomotion includes the skills that are necessary for the sensorimotor coordination of one's own body with her immediate surroundings. When we locomote, we monitor obstacles, identify terrain and surfaces, and direct our movements towards surrounding landmarks as beacons (Montello, 2005). In contrast, wayfinding is directed to remote destinations beyond one's current perception. During wayfinding, we typically plan and make decisions in order to reach these remote destinations. Because wayfinding relies to a large extent on spatial information that is not in our immediate surroundings, it is often driven by information that is stored externally (i.e., aided wayfinding). For example, we can use navigation applications or other types of spatial symbology to find our way. Wayfinding can also rely on information that is stored internally (i.e., unaided wayfinding). For example, we can commute to work along a familiar route using long-term memory (Montello, 2005). The skill with which we acquire spatial knowledge enables us to act autonomously in space without relying on digital aids. For example, we might use spatial knowledge to plan routes, to give directions to others, or to point to places that are not visible from our current location (Ishikawa, 2018). Accordingly, one of the key issues in navigation research is the manner in which humans and other animals acquire knowledge of their surroundings (G. L. Allen et al., 1996; Hegarty et al., 2006; Siegel & White, 1975; Thorndyke & Hayes-Roth, 1982; Golledge, 1999).

2.1.2 Mental information processes during navigation

Hegarty et al. (2006) specified the perceptual and cognitive processes according to their principle functions for spatial learning during navigation. Figure 2 provides an overview of these information processing functions including encoding, maintenance, inference, and readout. I will use this framework to introduce the cognitive processes that are involved during navigation and spatial learning.

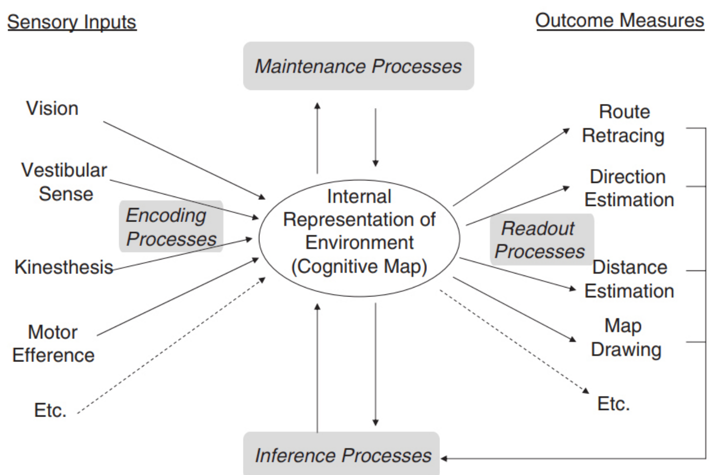


Figure 2: Overview of encoding, maintenance, inference, and readout processes during spatial information processing. Image source: Hegarty, Montello, Richardson, Ishikawa, and Lovelace (2006)

"Encoding" concerns the perception of spatial information that we receive from our surroundings via several channels and their initial processing . Humans' dominant sensory channel for encoding during navigation is vision. The human brain is remarkably efficient at assessing visible spatial relations, but receptors in the muscles and joints also support orientation with kinesthetic information regarding the relative positions of the head and limbs. In addition, the vestibular system in the inner ear detects linear and angular accelerations of the head and can be used to estimate movement speed and direction (Péruch et al., 1999). The congruence of these various perceptual inputs provides humans with the ability to assess their own movement through space efficiently. However, to encode spatial knowledge during navigation, humans do not always depend on all of these sensory channels simultaneously (Wang & Spelke, 2000). For example, individuals without visual impairment can efficiently construct spatial knowledge from visual information alone (e.g., Patrick Péruch & Wilson, 2004).

In order to keep track of our location in relation to a larger environment, we need to maintain mental spatial representations of objects in our immediate surroundings. Walking stairs, turning into a street, and avoiding collisions with pedestrians are remarkable skills that rely on the abilities to maintain and quickly access these spatial relations (Riecke, Heyde, & Bülthoff, 2005). In general, the perceptual and cognitive processes that maintain one's spatial relations to the surroundings are often referred to as spatial updating. However, spatial updating has been defined in a variety of ways (Wang, 2017). For example, humans and animals use internal (e.g., kinesthetic and vestibular information) and external (e.g., vision and optic flow) perceptual cues (e.g., travel velocity and turns) to track the movement of their own body in space and adjust the mental representation of its direction and position (Wang, 2017; Klatzky, Loomis, Beall, Chance, & Golledge, 1998; Loomis et al., 1993). Path integration is one particular type of spatial updating and refers to the use of self-motion estimation to update the mental representation of a homing vector towards a single target as one moves. This process enables navigators to spontaneously return home from any current location via a direct, novel route (Montello, 2005; Wehner, 2003; Wan, Wang, & Crowell, 2012). Interestingly, some evidence has shown that path integration may be involved in the contraction of coarse survey knowledge as well (Kearns et al., 2002; Foo et al., 2005).

Together, encoding and maintenance processes demonstrate that humans can construct mental representations of space by relying on different sources of sensory information. With spatial updating, humans can remain oriented and integrate separate egocentric experiences in order to learn the layout of a larger environment. Empirical evidence suggests that our ability to infer spatial relations from these egocentric experiences is an important skill for learning environmental spaces (e.g., Hegarty et al., 2006; Siegel & White, 1975; Colle & Reid, 1998; Sholl & Fraone, 2004).

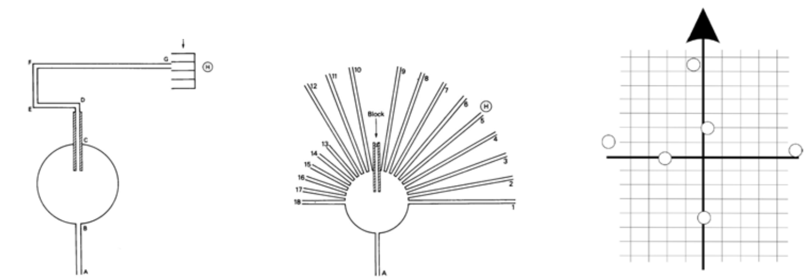
2.1.3 Acquiring spatial knowledge

Much research on the nature of long-term mental representations about environments has been strongly influenced by the idea of the "cognitive map" that was coined by Tolman (1948). Even though Tolman (1948) did not think of the cognitive map as a mental spatial representation necessarily, his results provided impetus to the field to study "map-like" knowledge that includes information regarding different locations and their relations (O'keefe & Nadel, 1978, p. 2). Tolman found that rats were capable of taking shortcuts in addition to learning simple stimulus-response associations when searching for food in mazes. In one of his experiments, Tolman, Ritchie, and Kalish (1946) trained rats to move from a starting point of a maze along a predefined route to a food target (Figure 3a). Following multiple training trials on this route, they tested rats' knowledge using a maze with radial corridors (Figure 3b) that provided the animal with a number of new directional choices, but the original path was blocked. Interestingly, many of the animals (36%) took the route that pointed in the Euclidean direction of the food rather than the corridor that was correct during learning. According to Tolman (1948), this result suggested a more comprehensive mental representation than simply associating specific actions with points along learned paths. In the following decades, the study of spatial representations of large-scale spaces in geography and psychology tended to propose spatial images (Lynch, 1960; Appleyard & Lintell, 1972) or maps (Downs & Stea, 1973) as the underlying structure of mental spatial representations (see Figure 3c).

2.1.3.1 Cognitive map

In support of such map-like representations, researchers have provided neuroscientific evidence of "place" cells in the hippocampus that primarily fire at a single specific location in space (O'Keefe & Dostrovsky, 1971). According to O'keefe and Nadel (1978), the core capability of the hippocampal cognitive map is that it stores information in its spatio-temporal context. Hence, the spatial location of an object is an integral part of its corresponding memory. Furthermore, memory in the cognitive map is ordered within a non-egocentric framework. Today, the non-egocentric framework defined by O'keefe and Nadel (1978) is often referred to as an allocentric reference frame (see Meilinger & Bulthoff, 2010). Importantly, this non-egocentric cognitive map suggests that spatial information from a three-dimensional, Euclidean space is integrated into an Euclidiean memory structure without a specific orientation (O'keefe & Nadel, 1978). By this definition, any directional or distance relationships among objects can be derived from a cognitive map, whether or not these relationships were encoded directly (O'keefe & Nadel, 1978). With the Euclidean metric as a fundamental characteristic of cognitive map representations, O'keefe and

Nadel (1978) challenged the widely held view of Piaget, Inhelder, and Szeminska (1960) that mental spatial representations advance from relative and topological (non-metric) to Euclidean and that the Euclidean representations only develop with much experience. Aligned with this Euclidean notion is evidence from subsequent studies that have identified cell firing in the entorhinal cortex that corresponds to topographical properties of multiple environmental cues rather a cue from any particular perceptual modality (Cressant, Muller, & Poucet, 1997; O'Keefe & Burgess, 1996). These findings support the view that the hippocampal system creates allocentric map-like representations of space (e.g., Hartley, Lever, Burgess, & O'Keefe, 2014). Some behavioral studies have also produced evidence that spatial information is represented in an allocentric manner. For example, in the visual Morris Water Maze (vWM) paradigm, participants are required to locate an invisible platform using external cues (e.g. salient objects). Many studies relied on the vMW paradigm and demonstrated that humans are able to locate hidden targets relative to landmarks or environmental geometry without any internal (i.e. kinesthetic) cues(e.g., Burgess, Spiers, & Paleologou, 2004; Doeller, King, & Burgess, 2008; Gardony et al., 2011).



(a) (b) (c)

Figure 3: (a) During the training phase of Tolman's experiment (Tolman, 1948), rats learned the maze from segment A to the food location at the end of segment G. (b) For testing the spatial knowledge of the rats, this radial maze was used. This maze has routes branching off of a central platform every few degrees (covering 180°). Most rats (36%) chose the route that directly pointed in the direction of the target. (c) A simplified illustration of a cognitive map with locations and metric relations represented in a common reference frame. (Image originally published in Meilinger, Frankenstein, Watanabe, Bülthoff, and Hölscher, 2015)

2.1.3.2 Critiques of the cognitive map

However, a variety of findings cast doubt on the metric assumptions that coincide with the cognitive map metaphor (see Warren, Rothman, Schnapp, & Ericson, 2017; Tversky, 1981; Wagner, 2008;

Schnapp & Warren, 2007) and suggest that empirical evidence for spatial memories of environments is better reflected by fragmented, distorted, and incoherent patchworks (Lee, 1970; Appleyard, 1970; Tversky, 1981). For example, route distance judgments of navigators change when movement is directed to the center or the periphery of a city (Lee, 1970). The perceived distance of a traveled route is also a function of the number of turns (Sadalla & Magel, 1980) and interactions along that route (Sadalla & Staplin, 1980). Similarly, Appleyard (1970) asked participants to draw maps of their hometown and found that the majority of these sketch maps (77%) showed great inaccuracies and distortions. Such findings conflicted with the claim that navigators construct a coherent map-like representation of the environment in their minds.

To account for the fragmentary nature of spatial representations, Siegel and White (1975) proposed a theory of spatial long-term memory in which the development of spatial knowledge progresses along three qualitative stages, from landmark to route to survey knowledge (Ishikawa & Montello, 2006, p. 94). One key assumption of this theory, based on Piaget and Inhelder (1956), is that spatial memory is non-metric or topological in the early stages of learning unfamiliar environments (Siegel & White, 1975). Only with substantial experience in an environment, humans can infer metric relations between objects and routes from direct experience of local objects and develop survey knowledge of the global surroundings. Over time, researchers have produced evidence against the strict stage-wise nature of spatial learning as described by this theory (e.g., Montello, 1998; Ishikawa & Montello, 2006). However, the majority of scientists from different fields (Golledge, 1999; O'keefe & Nadel, 1978; Hartley, Maguire, Spiers, & Burgess, 2003) agree with the distinction between the two fundamental types of spatial representation in long-term memory (i.e., action-oriented route knowledge versus metric survey knowledge) suggested by Siegel and White (1975).

2.1.3.3 Route knowledge

Route knowledge can be understood as the representation of sequences of associations between sensory events and actions (e.g., Siegel & White, 1975; Golledge, 1999). For example, route knowledge may be composed of turning directions for a series of intersections with different landmarks that were experienced during navigation. Route knowledge is often described as action-oriented in that specific behaviors (e.g., "turn left") are triggered when a familiar landmark or location is reached (Montello, 1998; Gillner & Mallot, 1998). A route representation can be conceived as sequence memory that provides navigation routines for the organism . By this definition, route knowledge does not provide navigators with information regarding Euclidean directions and distances and would not be sufficient for difficult navigation tasks such as taking a novel shortcut. However, route knowledge does support navigation behavior on well-learned routes (Meilinger, 2008).

2.1.3.4 Survey knowledge

Siegel and White (1975) observed that children with increasing age develop the ability to reconstruct spatial arrangements with high inter-object accuracy. Similar to the cognitive map notion, survey knowledge knits together experiences of landmarks and routes into a structure (i.e., a network-like assembly) that represents the configuration of space in a common coordinate system (Siegel & White, 1975). Siegel and White (1975) initiated the term survey knowledge to describe a quality of spatial mental representations with configurational (e.g., graphic skeleton between different objects) and metric properties. For example, the skeletal structure that interconnects routes and places allows one to easily plan routes and combine information from different trips. The metric underpinning of survey knowledge provides a navigator to accurately point with her finger to different places of a city, without having a map.

In the last decades, the cognitive map metaphor and the distinction between route and survey knowledge had strong impacts on spatial cognition research. However, there are several issues associated with these concepts that are still debated.

2.1.4 Oriention-specificity of spatial knowledge

One shortcoming of both survey knowledge and cognitive maps is that they do not account for the increasing evidence that spatial information is orientation-specific. A large amount of prior evidence shows that spatial recall (e.g., pointing in the direction of learned locations) improves when one's test perspective is aligned with the learning perspective. These findings suggest that spatial knowledge is anchored in, and aligned with, egocentric experience (i.e., an egocentric reference frame) (e.g., Waller, Montello, Richardson, & Hegarty, 2002; Klatzky et al., 1998; Burgess et al., 2004; Shelton & McNamara, 1997; Diwadkar & McNamara, 1997; Nardini, Thomas, Knowland, Braddick, & Atkinson, 2009). Similar to the influence of the egocentric perspective, other studies have demonstrated that the orientation of spatial memory can be determined by salient environmental features (e.g., walls of a room that are redundant for the task) (Shelton & McNamara, 2001; Burgess et al., 2004; Mou & McNamara, 2002). Importantly, all of these studies contested the notions of the cognitive map and survey knowledge because they had assumed that spatial representation is orientation-independent. While researchers still debate which factors determine the orientation of spatial memories (e.g., J. Li, Xie, & Zhao, 2019), there is much agreement that spatial information is stored with a preferred orientation, regardless of its source (e.g., maps or direct experience) or scale (e.g., large or small) (Montello et al., 2004, p. 277).

> **Key findings about spatial memory**
>
> Much research has relied on the understanding of spatial knowledge as action-based memory of well learned routes (route knowledge) and metric memory that is map-like (cognitive map). While this dichotomy is still widely accepted, there is many open questions about what causes the fragmentary nature of spatial representations, and when spatial memory is metrically accurate and when it is not.

2.2 THE SCALE OF SPACE

Siegel (1981) proposed that there might be inherent differences between the mental encoding of spaces that one can perceive from a single glance and the mental encoding of spaces that must be learned in segments from multiple perspectives and segregated over time. To develop my argument about why the mental integration of locally and globally visible landmarks into survey representations is different, the following section will deal with psychological scale and its relevance for mental spatial representations. While we can perceive the layout of a room from a single viewpoint, imagine the many views needed to see all of the places in a city and build up a mental representation of it. One of the challenges of learning the layouts of large-scale environments is to mentally relate these many perspectives in a coherent manner over time. From a cognitive perspective, it is essentially this sequential mode of information processing (compared to a simultaneous mode) that is crucial for investigating spatial learning in general, and to understand landmark integration in particular.

2.2.1 Taxonomy of psychological spaces

Montello (1993) defines four types of psychological spaces in terms of scale: *figural*, *vista*, *environmental*, and *geographical space* (Montello, 1993; cf. Freundschuh and Egenhofer, 1997). This model is organized with respect to the manner in which an observer can apprehend a particular space. *Figural space* is smaller than the human body, including the spaces of small objects and pictures (and not necessarily the spaces they represent) (Montello, 1993, p.315). A cartographic map can be considered part of a *figural space*. An important psychological property of *figural space* is that the spatial relations between multiple objects can be assessed from a single viewpoint within a relatively short amount of time. Similarly, vista spaces are defined as the spatial surroundings of an observer that are visible from his or her viewpoint. Examples of vista spaces include a single room or a city square. In contrast to figural and vista spaces, environmental spaces are at the scale of neighborhoods, quarters, and cities and require an observer to move over a considerable amount of time to fully apprehend it (Montello, 1993). Finally, geographical spaces (e.g., a country) are so large that we can only apprehend them via symbol systems like maps. It has to be noted that besides the psychological scale of space, the physical scale of space may also be important for spatial cognition (e.g., see Padilla, Creem-Regehr, Stefanucci, & Cashdan, 2017).

2.2.2 Local and global representations of space

In recent decades, the importance of the psychological scale of space is increasingly recognized as a fundamental consideration in spatial cognition research. Accordingly, several researchers have proposed that the memory system for figural space is psychologically distinct from the memory system of vista and environmental spaces (e.g., Hartley et al., 2003; Hegarty et al., 2006; G. L. Allen et al., 1996; Wolbers & Hegarty, 2010). Indeed, factor analyses have been used to suggest that individual performances on pencil-and-paper tests (i.e., in figural space) and on navigational tasks (i.e., in environmental space) load on different factors (G. L. Allen et al., 1996; Lorenz & Neisser, 1986). Similarly, neuropsychological studies have reported evidence of patients with selective deficits in spatial tasks based on either figural or vista spaces (Piccardi, Iaria, Bianchini, Zompanti, & Guariglia, 2011).

In accordance with these results, empirical data that examined spatial learning during navigation support the notion that local spatial information is not easily integrated into existing representations of a larger scale environment (Chrastil & Warren, 2013; Colle & Reid, 1998). For example, Colle and Reid (1998) demonstrated that navigators can learn metric spatial relations for their local surroundings very quickly but needed more time to develop a metric representation of the relations between them. Colle and Reid (1998) suggested that, while the encoding of vista spaces is perceptually-driven and mental integration involves direct imagery, the encoding of environmental spaces relies on indirect imagery and mental integration involves more attentional resources. Consequently, heavy attentional load may result in errors and rather imprecise stimulus-action associations (Colle & Reid, 1998). Similarly, Wang and Brockmole (2003) investigated if participants could easily integrate an unfamiliar local surrounding into their representation of a familiar campus environment. After participants learned an arrangement of objects in the laboratory, they were disoriented and asked to point towards both the laboratory objects and landmarks from around the familiar campus. This study found that participants made larger errors when judging the directions of campus landmarks compared to laboratory objects. This finding suggests that humans maintain multiple representations for nested environments and that these representations are not necessarily well integrated.

Researchers have also investigated whether navigators were better at spatially relating within- or between-environment experiences in memory (Ishikawa & Montello, 2006; Schinazi, Nardi, Newcombe, Shipley, & Epstein, 2013). For example, Weisberg et al. (2014) asked participants to learn eight landmarks along two routes of a virtual environment. After learning all eight buildings, participants navigated on two paths connecting these routes to each other. They found that pointing error on within-route trials was significantly lower than error on between-route trials.

To account for these effects of psychological scale, some researchers have proposed hierarchical knowledge structures such as topological spatial knowledge based on a node-graph analogy (e.g., Hübner & Mallot, 2002; Chrastil & Warren, 2014; Meilinger, 2008; Warren et al., 2017). According to these theories, a node represents a memorized location and an edge represents a route or turning action that is associated with this location (Meilinger, 2008). For example, Chrastil and Warren (2014) defined graph knowledge as follows:

> What we will call graph knowledge is situated between route and survey knowledge. A purely topological graph of an environment consists of a network of place nodes (identifiable places, including junctions) linked by path edges (traversable paths between nodes). Thus, graph knowledge would express the known connectivity of the environment, enabling novel detours. In contrast, route knowledge does not accommodate multiple paths intersecting at a junction or multiple connections between the same locations, making detours difficult.
> (Chrastil & Warren, 2014, p. 1)

Recent empirical evidence has supported the relevance of topological knowledge to mental spatial representations using "impossible virtual environments" (Muryy & Glennerster, 2018; Warren et al., 2017). In these experiments, invisible portals were placed in hallways and seamlessly transferred participants to a different location within the same environment. After participants were exposed to these metrically incoherent environments, most theories of survey knowledge would predict no short-cutting behavior because short-cutting is assumed to rely on a metric spatial representation. While participants in these studies did not perform well on survey knowledge tasks (i.e., tasks that measure metric properties of mental representations), they were able to find shortcuts efficiently using the available landmarks (Warren et al., 2017).

These findings casted doubt on the assumption of survey knowledge that environmental space is mentally represented in a metric coordinate system (Siegel & White, 1975; O'keefe & Nadel, 1978; Poucet, 1993). While navigators may quickly acquire metric knowledge within vista spaces (Ishikawa, Fujiwara, Imai, & Okabe, 2008; Collett & Lehrer, 1993), they develop relatively coarse spatial networks to mentally connect these distant places in the representation of an environmental space due to attentional limitations (Meilinger et al., 2014; Chrastil & Warren, 2014). According to these frameworks, the notion of route knowledge remains important for the representation of space in higher level structures (e.g., in a network that connects vista spaces; Meilinger et al., 2014; Mallot, 1999. For example, Figure 4 illustrates the network of reference frames model (Meilinger, Frankenstein, Watanabe, Bülthoff, & Hölscher, 2015) and the labeled graph model (Warren et al., 2017) that both use graph-like metaphors to describe the manner in which local metric knowledge of vista spaces is combined into larger mental representations. Meilinger et al. (2014) proposed that metric knowledge is stored in long term memory only for vista spaces. Accurate metric judgments between different vista spaces rely on temporarily combining memory of local spaces using egocentric perspective shifts (see Figure 4a). Similarly,Warren et al. (2017) proposed a labeled graph as a mental spatial representation with multiple place-nodes that are labeled using metric information. The local metric information, however, is defined only on the lower level of representation (see Figure 4b).

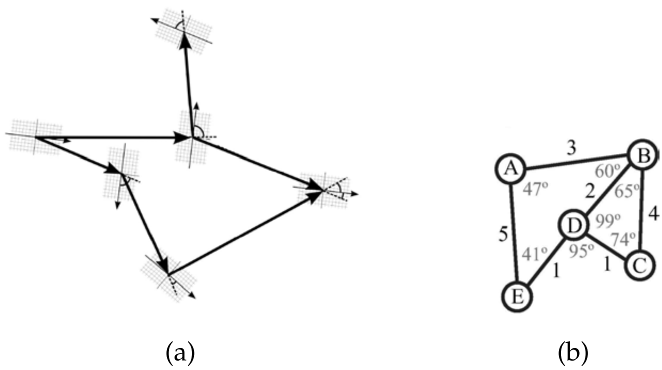


Figure 4: Illustrations of the network of reference frames model (Meilinger, Frankenstein, Watanabe, Bülthoff, & Hölscher, 2015) and the labeled graph model (Warren, Rothman, Schnapp, & Ericson, 2017)

Notably, researchers still debate whether (or in which situations) between-vista spatial relations are mentally represented topologically in multiple reference frames or as part of a single global reference frame with local metric distortions. For example, recent research provided compelling evidence in support of global and local reference frames that are learned simultaneously in the same room-size environment (Greenauer & Waller, 2010). Such evidence is in accordance with theories that propose that spatial knowledge can be encoded metrically in memory but organized within hierarchies (e.g., Hirtle & Jonides, 1985; McNamara, Sluzenski, & Rump, 2008). For the present thesis, however, the key insight from the research presented above is the strong link between spatial scale and the difficulty of acquiring metric spatial knowledge. From these findings, I expect that metric knowledge in local vista spaces is represented more accurately than for environmental spaces.

Key findings about the importance of spatial scale for memory of space

Empirical evidence demonstrated increased efficiency in acquiring metric knowledge of local vista spaces as compared to global environmental spaces during navigation. While humans can acquire metric knowledge for local surroundings very quickly, metric knowledge for the global environment is acquired only slowly, if at all. Researchers proposed that increased cognitive demands of integrating local environments into global representations cause these observed differences. The present thesis takes these insights as a starting point to investigate the mental integration of local and global landmarks.

2.3 WORKING MEMORY

To uncover the source of these scale-dependent variations in spatial memory, some researchers have pointed to the key role of WM for learning during navigation (Hegarty et al., 2006; G. L. Allen et al., 1996; Sholl & Fraone, 2004). There is a multitude of theoretical frameworks that address the definition of WM and the manner in which it supports human reasoning and behavior (for a review see Baddeley, 2012). Most researchers agree that WM can be conceived as the cognitive resources that are devoted to short-term *storage* and *processing* of information (Barrouillet, Portrat, & Camos, 2011).

Storage describes the function of WM to keep information temporarily active and retrievable when it is no longer perceptually present. For example, to combine current with past navigation experience, we need to temporarily retain information regarding your location in relation to the larger environment. The storage functions of WM provide cognitive resources for rendering mental content retrievable. In the context of navigation, it has been proposed that sequences of route directions might be retained in verbal WM (G. L. Allen et al., 1996) and that configurations of landmarks might be retained in visuospatial WM (Hegarty et al., 2006).

Processing describes the function of WM to transform and combine information according to one's needs (Barrouillet et al., 2011). For example, one might take a walk through a city quarter and follow some unfamiliar streets until she recognizes a place that she once visited. Using the processing functions of WM, a navigator can integrate novel experiences within his or her existing spatial knowledge.

2.3.1 Limited capacity system

Notably, the active processing of information in WM is limited. With the increasing demands of a task, we risk exceeding the limits of available WM resources and consequently failing to process information accurately and efficiently.

Existing accounts of WM can be divided into two distinct categories. Domain-general accounts assume a single and limited attentional resource. These accounts claim that processing and storage functions are not independent but draw on the same limited resource (i.e., attention) (e.g., Barrouillet et al., 2011). According to these accounts, attentional resources are required for maintaining information (storage) and for transforming or combining information (processing). Thus, performing a processing and a storage task simultaneously would require attentional resources to be shared dynamically by, for example, using task-switching strategies.

In contrast, domain-specific accounts define independent resource pools for processing and storage functions (Baddeley & Hitch, 1974; Baddeley, 2000, e.g.,). According to these accounts, interference between these processes should only occur when drawing on resources from the same subsystems.

2.3.2 The visual and spatial subsystem

The most influential domain-specific model was originally developed by Baddeley and Hitch (1974). In their experiments, Baddeley and Hitch (1974) observed that participants' memory performance was impaired after a dual-task condition compared to the single-task condition. However, because these researchers did not observe performance variations attributable to the dual-task condition for some situations, they figured that WM must provide multiple resource pools (Baddeley & Hitch, 1974). Specifically, they posit that the phonological loop and the visuospatial sketchpad temporarily store verbal and visuospatial information, respectively. Each of these two subsystems is thought to have a limited storage capacity that restricts the number of items that individuals can hold in these subsystems at any one time (Baddeley, 2000). Using an attentional control system (i.e., the central executive), one is capable of retrieving information from the two storage systems. When combining verbal and visuospatial information across modality, humans rely on a domain-general store that is called the episodic buffer (Baddeley, 2000).

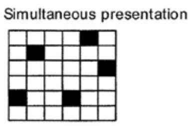
Recently, there has been increasing empirical evidence that supports a further subdivision of the visuospatial sketchpad into visual and spatial components that are partly independent of each other (Darling, Della Sala, & Logie, 2007; Logie & Marchetti, 1991). Originally, this distinction was supported by experimental data that indicated a dissociation between the processing of the visual appearance (e.g., color and shape) and the locations of items presented on a computer screen. For example, Logie and Marchetti (1991) found that a spatial concurrent task uniquely impaired memory of the sequence of stimuli as experienced in space. In contrast, a visual concurrent task uniquely impaired memory of the color hue of the items. Further support for this dissociation between visual and spatial components can be found in patients with selective deficits for encoding visuospatial stimuli that are presented either sequentially or simultaneously (e.g., Wansard et al., 2015). In addition, some researchers have proposed that spatial information that is encoded sequentially relies more on spatial WM and that simultaneous encoding tends to rely more on visual WM (Lecerf & De Ribaupierre, 2005). Sequential viewing refers to the successive presentation of objects one at a time. Hence, a learner cannot simultaneously perceive the spatial pattern or configuration of objects as visual input but needs to reconstruct it from single instances that are presented over time. Simultaneous viewing refers to the presentation of multiple spatial locations at the same time. During simultaneous viewing, the spatial pattern can be visually perceived.

In accordance with the proposal of Lecerf and De Ribaupierre (2005), evidence from dual-task studies have shown how spatial and visual WM are involved during the acquisition of spatial knowledge from either direct navigation or map learning, respectively (Coluccia, Bosco, & Brandimonte, 2007; Labate et al., 2014; Gras et al., 2013; Wen et al., 2011, 2013; Meilinger et al., 2008). In general, these studies showed that dual-task conditions had a negative effect on spatial knowledge acquisition. However, learning impairments due to spatial secondary tasks (spatial WM) were relatively low if object-to-object relations could be encoded simultaneously from a single viewpoint, such as when learning landmarks from a map (Coluccia et al., 2007). Learning impairments due to spatial secondary tasks were relatively high if object-to-object relations required sequential integration, such as when landmarks were only visible locally and navigators perceived one at a time from different locations (Gras et al., 2013; Labate et al., 2014; Wen et al., 2013).

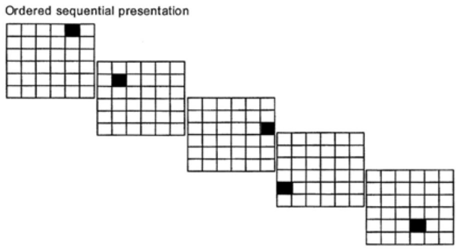
2.3.3 The advantage of viewing spatial relations simultaneously

Importantly, a majority of research involving *figural space* indicated an advantage for spatial memory performance after configurations of objects were presented simultaneously rather than sequentially. For example, Blalock and Clegg (2010) and Lecerf and De Ribaupierre (2005) employed a change detection paradigm in which participants were asked to judge whether learning and test arrays were identical. The arrays in the study of Lecerf and De Ribaupierre (2005) consisted of multiple locations that were presented either sequentially or simultaneously in a matrix. In both studies, participants demonstrated improved recognition performance after learning in the simultaneous condition. For example

Lecerf and De Ribaupierre (2005) asked participants to memorize the locations of the filled cells in two conditions. In the simultaneous presentation condition (Figure 5a), multiple locations were presented at the same time. In the sequential presentation condition (Figure 5b), the locations were presented one at a time. They found that recognition of the correct spatial pattern was better after simultaneous presentation than after sequential presentation.



(a)



(b)

Figure 5: Sequential and simultaneous viewing of spatial information. Image source: Lecerf and De Ribaupierre (2005)

A spatial memory advantage for information that was presented simultaneously was also empirically shown in vista spaces. Lupo et al. (2018) found that when participants walked a room-sized platform that displayed locations in a matrix, simultaneous presentation also led to improved memory performance. These findings from very controlled, but somewhat artificial environments support the simultaneous processing advantage for spatial memory. For the objectives of the present thesis, the issue of whether these results can be transferred to navigation and spatial learning in environmental spaces remains.

There is some evidence from navigation research that hints towards a memory advantage after processing spatial information in a simultaneous manner. For example, it has been shown that participants who learned environments from maps understand inter-object relations better than participants who learned such relations from navigation through the environment (Thorndyke & Hayes-Roth, 1982; Zhang, Zherdeva, & Ekstrom, 2014). For example, Zhang et al. (2014) could show that map learning led to significantly faster improvements in survey knowledge accuracy than did learning from navigation. However, other studies could show that this advantage only occurs when participants use static maps with a fix reference frame ((e.g., north-up paper map; Ishikawa et al., 2008) which supports the development of orientation-specific spatial memory (Meilinger, Frankenstein, Watanabe, et al., 2015). In contrast to the fixed orientation of north-up paper maps, one's egocentric perspective constantly changes during body movement, so allocentric inter-object relations should be more difficult to encode or memorize during navigation (Fisk & Sharp, 2003). While these insights indicate an advantage of simultaneous processing they cannot rule out the possibility that the fixed reference frame or the top-down perspective of the map caused the memory advantage rather than simultaneity per se.

To my knowledge, only two navigation studies have directly examined the learning effects of sequential and simultaneous encoding of objects during navigation from a first-person perspective. Meilinger, Strickrodt, and Bülthoff (2016) and Ruotolo et al. (2012) compared memory for object-to-object relations after the sequential or simultaneous presentation of objects in room-sized spaces. Sequential processing was operationalized by blocking the lines of sights between the objects with walls that required learners to move. Confirming prior findings from figural spaces, Meilinger, Strickrodt, and Bülthoff (2016) found that simultaneous learning in vista spaces resulted in higher accuracy for object-to-object relations than sequential learning in environmental spaces that required movement. Similarly, Ruotolo et al. (2012) found that metric distortions in spatial memory were more pronounced when information was learned sequentially and that these distortions accumulated as the spaces increased in size (i.e., spatial scale). However, because cognitive processes change with spatial scale (Montello, 1993; Shelton & Gabrieli, 2004), it is still unclear if the benefits of simultaneous presentation over sequential presentation hold for larger environmental spaces such as a city.

There are at least two different explanations for the spatial memory advantage of simultaneous presentation, including the flexibility of the order with which items can be attended (Lupo et al., 2018; Mackworth, 1962) and the relational organization of visuospatial WM (as opposed to item-focused organization; Jiang, Olson, & Chun, 2000; Blalock & Clegg, 2010). According to the flexibility explanation, this memory advantage emerges from the conditions that positions can be scanned several times and in one's preferred order during simultaneous presentation (Lupo et al., 2018; Mackworth, 1962) but not during sequential presentation. The relational organization explanation assumes that stored spatial information is memorized as parts of configurations rather than as absolute locations in space (Blalock & Clegg, 2010; Jiang et al., 2000; Lecerf & De Ribaupierre, 2005).

2.3.4 Working memory capacity

The ability to orient and develop spatial knowledge of environmental spaces differs substantially between individuals (Wolbers & Hegarty, 2010; Ishikawa & Montello, 2006). Traditionally, measures of spatial ability included paper-and-pencil tasks such as mental rotation, the search for hidden figures, mental paper-folding, or tasks that measure spatial WM capacity. Recent evidence indicated that performance on these tasks might reflect a set of spatial abilities that is partially dissociated from the abilities that are required for learning environmental spaces via real-world navigation (Hegarty et al., 2006), which involves multi-sensory processing (e.g., vestibular and kinesthetic). In an approach to model the relation between small- and large-scale spatial abilities, Hegarty et al. (2006) found that shared variance between these two sets of abilities is specific to spatial representations constructed from visual inputs (see Figure 6).

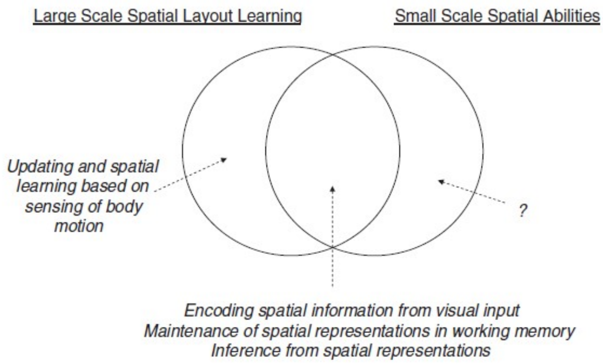


Figure 6: Hegarty, Montello, Richardson, Ishikawa, and Lovelace (2006) found compelling evidence for a partial dissociation between measures of small-scale spatial abilities and measures of learning from navigating environmental spaces. This study suggests that the common mechanisms of both sets of abilities are specific to the mental processing of visual information. Note that her model does not define which processes are specific to small-scale spatial abilities. Image source: Hegarty, Montello, Richardson, Ishikawa, and Lovelace (2006)

The dissociation between learning from real-world navigation and learning from visual media reflects the different demands of these information sources on the internal maintenance of spatial information (Hegarty et al., 2006). For example, when vestibular, kinesthetic, and/or motor-efferent signals indicate self-motion (i.e., during real-world navigation), participants employed spatial updating automatically without relying on attentional resources from WM (Riecke, Heyde, & Bülthoff, 2005). In contrast, spatial updating based on visual information alone is rather effortful, drawing on participants' attentional resources in WM (Riecke, Heyde, & Bülthoff, 2005).

Hence, one important consideration for acquiring survey knowledge from visual information is the limitation of WM resources. Prior research has indicated that individual differences in WM capacity are correlated with peoples' abilities to acquire survey knowledge (e.g., Münzer, Zimmer, Schwalm, Baus, & Aslan, 2006). More specifically, a study by Fields and Shelton (2006) could demonstrate that survey knowledge acquisition from route perspective (i.e., first-person perspective) puts higher demands on WM and perspective taking processes than encoding from survey perspective (e.g., learning from a map). They figured that learning from egocentric perspective puts additional cognitive load on participants who need to infer and maintain a global structure from egocentric encoding. However, when participants learn spaces from a survey perspective, they simply need to rehearse the previously seen relative locations in WM (Fields & Shelton, 2006). Accordingly, they could show that the acquisition of survey knowledge from egocentric encoding relied more strongly on perspective taking ability than from survey encoding (Fields & Shelton, 2006). With regard to this, it is surprising that no research has looked into the specific relations between WM capacity/perspective taking ability and the learning local or global landmarks.

So-called "complex span tasks" assess WM capacity as the joint visuospatial processing and storage capacities of the WM system (Barrouillet et al., 2011). Typically, such tasks have concurrent processing and storage requirements. For example, participants may have to remember arrays of locations and concurrently process irrelevant information from a 2D plane. Because of their concurrent processing and storage requirements, performance scores in complex span measures indicate the efficiency of the central executive in controlling transformations between storage resources (Unsworth & Engle, 2007; Mulligan & Peterson, 2008). Thus, investigating the relation between WM capacity and spatial learning may help to elucidate the underlying cognitive processes of spatial learning based on sequentially visible local or simultaneously visible global landmark configurations.

2.3.5 Extended definition of survey knowledge for the present thesis

In this thesis, I will use the term survey knowledge to refer to an integrated mental representation (e.g., including landmarks and routes) that is spatially organized within a hierarchical memory structure. High accuracy of inter-object spatial judgments reflects high spatial accuracy for local metric knowledge and its' global integration. This definition serves the thesis to reasonably assess participants' performance to integrate landmarks into some type of common configurations. While some theories suggest that the integration of local memory structures into a global representation occurs at recall rather than encoding, this distinction does not affect the results of the studies presented in this thesis.

Key findings about simultaneous and sequential encoding of spatial information in WM

WM is a capacity limited system that provides the cognitive resources for short-term processing and storage of spatial information. Prior research indicated that learning from navigation during which information is presented sequentially involves different WM processes than

> map learning during which information is presented simultaneously. Importantly, a majority of evidence indicated a spatial memory advantage when information is encoded simultaneously. However, only a few studies examined the simultaneous and sequential learning of landmark information in environmental spaces. The present thesis aims to close this gap and also employs individual WM capacity measures that might help to elucidate the role of WM during sequential and simultaneous spatial learning.

2.4 THE FUNCTIONS OF LANDMARKS

The present thesis defines landmarks as point-like visible features that are either located along the route or in the distance (Klippel & Winter, 2005) and can be viewed locally, from within a limited area of the route, or globally, from a large part of a city environment (Castelli et al., 2008; Steck & Mallot, 2000). Local landmarks are defined as being sequentially (locally) visible from a given route. Global landmarks are defines as being simultaneously (globally) visible from a given route. In contrast to our definition, some researchers define local landmarks as proximate landmarks that provide accurate positional information, and global landmarks as distal landmarks that provide stable directional information (Lynch, 1960; Gardony et al., 2011). In accordance with both definitions, a large portion of prior research has approached landmarks from a perceptual perspective and examined the physical and cognitive determinants of landmarks (Hirtle & Jonides, 1985). This research has defined several physical characteristics that are important for making an object in the environment useful as a landmark for navigation. Among these properties are objects' visual appearance, their constant reliability, and their locations in space. The description of these physical features was often used to examine the probability with which a salient object would become a landmark that could be used spontaneously during navigation. In addition to landmark salience, researchers can also examine the manner in which the perceptual properties of objects affect their utility for a given task and in a given navigational context. The present thesis focused on this latter aspect of locally and globally visible environmental objects. With a similar goal in mind, Chan, Baumann, Bellgrove, and Mattingley (2012) proposed a landmark taxonomy that provides an overview of the various functions of landmarks in specific navigation contexts. They distinguished between landmarks as navigational beacons, orientation cues, associative cues, and reference objects.

2.4.1 Beacons

A landmark serves as a beacon when it provides a highly reliable cue for a single specific goal location Chan et al. (2012). For example, one can use the visibility of a skyscraper in a city as a beacon to memorize it or to navigate towards it, irrespective of other environmental information. Beacon-following emerges very early in human development (MacDonald, Spetch, Kelly, & Cheng, 2004) but has been found to impair the learning of other potentially relevant spatial information (e.g., Hardt & Nadel, 2009).

2.4.2 Associative cues

Environmental objects can also be helpful for remembering navigation-related actions (Chan et al., 2012). For example, one can use a salient building to remember where to turn into a street to get back home (Steck & Mallot, 2000). Landmarks as associative cues are evident in improved route knowledge acquisition for paths that have salient objects (Waller & Lippa, 2007). Importantly, using landmarks as associative cues for navigation relies on response learning and is typically not associated with survey knowledge acquisition (see Section 2.1).

2.4.3 Orientation cues

Landmarks can be considered orientation cues when they are used to provide information about one's own orientation in the environment Chan et al. (2012). For example, a salient mountain ridge on the horizon may be used to remember the orientation of a street. The importance of orientation cues for spatial learning is supported by the identification of head-direction cells that are activated according to an animal's heading during navigation but independent of its location within the environment (Taube, 1998). Staying oriented during navigation is important for acquiring accurate survey knowledge because to-be-learned objects are often not mutually visible. In such cases, maintaining orientation will improve integration of objects between vista spaces.

2.4.4 Reference objects

Landmarks can function to provide navigators with position, associative, and orientation information in environmental spaces. Building on these more basic functions, research has also suggested that landmarks help people mentally structure the vast amount of spatial information that is available in the environment and support the efficient acquisition of survey knowledge (Presson & Montello, 1988; Sadalla et al., 1980; Sorrows & Hirtle, 1999; Golledge, 1999; Couclelis et al., 1987). For example, humans can remember environmental locations according to reference landmarks to develop and access spatial knowledge more efficiently (Sadalla et al., 1980). From this research, selective landmarks seem to support survey knowledge acquisition by providing a mental spatial anchor (i.e., a spatial reference point) that is used to organize the encoding and integration of other spatial information during learning (Mou, McNamara, Valiquette, & Rump, 2004; Chan et al., 2012). In this context, the connection between the benefits of landmarks for spatial learning and their visibility within the environment becomes an important issue. Is survey knowledge acquired more efficiently if learners have global visual access to landmarks? Following this line of reasoning, researchers investigated the importance of globally visible landmarks for navigation and spatial learning.

2.5 GLOBAL LANDMARKS

One branch of research has shown that the display of distant landmarks on digital navigation assistants support in situ orientation and the recall of survey knowledge (R. Li et al., 2014; Schwering et al., 2017). These studies examined global landmarks as salient and often popular objects or areas (e.g., city center) that are not necessarily visible from one's location. A navigator's prior knowledge about these objects or areas could be used to provide assistance for global orientation in familiar environments. In contrast, the approach of the present thesis was to understand the spatial learning benefits of navigators with regular visual access to a set of landmarks in an environment where they have no or very little prior knowledge.

Therefore, the present thesis defined the term "global landmark" as an environmental object that is highly salient and visible from many points within an environment. A stereotypical example is the Eiffel tower or any skyscraper that is visible from many points along a traveled route. Employing concepts from Montello's taxonomy of psychological scale (see Section 2.2), a globally visible landmark is part of many different vista spaces along a route simply because it is visually accessible. In contrast to global landmarks, visual access to local landmarks is restricted to the surroundings near an observer. For example, a view of low-rise architecture is typically obstructed by surrounding buildings. Hence, one can see these buildings only during short segments of a travel or from within a single vista space. Previous research has shown that humans pay attention to the local and global aspects of environments for navigation (Coluccia et al., 2007; Gardony et al., 2011, e.g.,) and route knowledge (Steck & Mallot, 2000). However, there is little research that has investigated the differences between locally and globally visible landmarks for survey knowledge acquisition in unfamiliar environmental spaces.

For example, Meilinger, Schulte-Pelkum, et al. (2015) had three groups of participants learn a virtual maze with seven local landmarks by navigating with either no global heading information, a single distant landmark (i.e., orientation cue), or a surrounding hall that could be used to infer one's own orientation and location (Meilinger, Schulte-Pelkum, et al., 2015). They found that all three groups had similar amounts of survey knowledge, and global heading information did not enhance spatial learning for local landmarks.

Castelli et al. (2008) had participants learn a virtual environment for 3 minutes in a guided exploration, and 10 minutes during free exploration. The very minimalist environment had local and global landmarks present simultaneously. Using egocentric pointing tasks after navigation, the authors found no differences between the accuracy of local and global landmark memory. However, in this study, each participants' survey knowledge consisted of only 3 pointing judgments overall. Each of these three trials included both, local and global landmarks (Castelli et al., 2008). Unfortunately, it is unclear how the researchers could accurately compare local and global landmark learning under these circumstances.

In H. Li et al. (2016), the researchers had participants learn the layout of virtual multi-level buildings with a number of windows through which participants had visual access to a global landmark from either a single floor or from two floors. As compared to Meilinger, Schulte-Pelkum, et al. (2015) and Castelli et al. (2008), their virtual environment had two floors. Their results showed that participants' between-floor pointing performance was reliably faster and more accurate in the two-floor visual access condition than in the single-floor visual access condition, suggesting that visual access to the global landmark enhanced users' development of an integrated mental representation (H. Li et al., 2016).

These studies suggest mixed evidence for the potential benefits of global landmarks for survey knowledge acquisition. One reason for the mixed results could be that none of these studies directly separated local landmark learning from global landmark learning. Another reason might be that participants in these studies were able to devote full attention to the spatial learning task (H. Li et al., 2016; Castelli et al., 2008; Meilinger, Schulte-Pelkum, et al., 2015). To our knowledge, no studies have separated the learning of local landmark configurations and compared it with the learning of global landmark configurations and examined both with respect to stress or high concurrent task demands. Stress factors are typical for urban navigation and might reduce a navigator's ability to encode spatial relations in WM. I argue that this is an important research gap because these contextual factors can impair cognitive functioning (see Section 2.7). Considering time- and attention-critical conditions, it is still unclear which landmarks are suited best for spatial knowledge construction. In Section 2.6, I will summarize relevant prior research regarding the influence of stress on WM and spatial learning.

Key findings about the role of landmarks for spatial learning

Landmarks can function to provide navigators with position, associative, and orientation information. However, prior research produced mixed evidence concerning the benefit of global landmarks for survey knowledge acquisition. To our knowledge, no studies have directly examined the effects of learning local or global landmark configurations with respect to the cognitive processing involved in working memory. The present research aimed to close this gap and directly compared survey knowledge acquisition of locally and globally visible landmarks when working memory was impaired by stress or concurrent task load.

2.6 PSYCHOLOGICAL AND PHSYIOLOGICAL STRESS

Stressful situations are common in everyday human life. For example, stress may arise when we are struggling with time pressure (Wahlström, Hagberg, Johnson, Svensson, & Rempel, 2002) with respect to being late for appointments (Zimring, 1981) or when our performance is evaluated (Zeidner, 1998). Some evidence even points to stress-related emotions that emerge during environmental navigation (Lawton, 1994) and may be associated with anxiety of becoming lost or disoriented (Bryant, 1982). Generally speaking, stress describes an experience that we all know from our everyday lives. As clear as a one's intuition regarding stress may be, there is little agreement in the scientific literature (for a review see; Sandi, 2013). Debates regarding how to define stress are long-standing. Some researchers view stress as physiological threats, including physical effort or sleep deprivation. Others defined stress as an adaptive response that is required by stressors that are threats to the homeostasis of an organism (Selye, 1976; Levine, 2005). Psychologists often define stress as subjective appraisals of threat (e.g., demanding situations) that lead to a complex psychophysiological response (Lazarus & Folkman, 1984). In the present thesis, I rely on a multidimensional definition of stress that incorporates cognitive, motivational, and emotional appraisals of a task and results in an combination of physiological and psychological responses that may last for a period of minutes to hours (Dhabhar & McEwen, 1997).

2.6.1 Subjective appraisal and physiological response

From a psychological perspective, it is important to consider interactions between the context, the individual, and the task that causes a stress response. Emotions such as stress result from subjective evaluations of events, and accordingly, the individual stress response reflects subjective appraisal processes, such as threat perception (Lazarus & Folkman, 1984), and the situational demands of a task, such as perceived workload (Matthews et al., 2013). The Dundee Stress State Questionnaire (DSSQ) is a self-report measure that has been used in a variety of fields and reliably assesses how individuals feel in the face of a given task or event. The methodological theory underlying the DSSQ is defined in Section 3.3.2.6.

At the physiological level, stress engages two neurobiological systems. First, stressors engage the sympathetic nervous system, which regulates vital physiological states such as changes in heart rate variability (Burg & Pickering, 2011) and sweat production (Boucsein, 2012). Second, stressors engage the hypothalamic-pituitary-adrenal axis, which is an endocrine system through which glucocorticoids are secreted (De Kloet, Joëls, & Holsboer, 2005). A major behavioral role of the activation of these systems is a short-term increase (from seconds to minutes) in energy production required for immediate survival (Sapolsky, 1992). However, immediate threats are not the only situations that manifest in physiological responses. Prior research has demonstrated that physiological stress reactions can be caused by social pressure (Kirschbaum, Pirke, & Hellhammer, 1993), time pressure (Wahlström et al., 2002), and many other situations or stimuli.

2.6.2 Valence and arousal

As we have seen, acute stress can be considered a psychophysiological phenomenon that occurs as a result of individual appraisal processes and leads to different motivational and physiological reactions in different people. Attempts to connect these various aspects have resulted in theories that define a small set of core dimensions (Russell & Barrett, 1999; Watson & Tellegen, 1985; Thayer, 1989). In the circumplex model of affect, the authors conceptualize a theory of emotion that is based on a fundamental distinction between a physiological state (i.e., *core affect*), and an experiential interpretation of core affect that allows humans to report their emotional experience and relate it to conditions, events, or persons in the world (i.e., *prototypical emotional episodes*). Russell and Barrett (1999) describe the relation between these two aspects as following:

> We use the term core affect to refer to the most elementary consciously accessible affective feelings (and their neurophysiological counterparts) that need not be directed at anything. Examples include a sense of pleasure or displeasure, tension or relaxation, and depression or elation. Core affect ebbs and flows over the course of time. Although core affect is not necessarily consciously directed at anything—it can be free-floating as in moods—it can become directed, as when it is part of a prototypical emotional episode.
> (Russell & Barrett, 1999, p. 806)

Russell and Barrett (1999) argue that there are various ways to divide prototypical emotional episodes into categories, but researchers could not agree on a set of basic categories. In contrast to the many attempts to define the basic categories of emotion (Ekman, 1992), Russell and Barrett (1999) aimed to understand the psychophysiological dimensions that underlie these multifaceted interpretations. With this approach, many researchers agree on at least two core dimensions that are often termed valence and arousal (Russell & Barrett, 1999; Watson & Tellegen, 1985; Thayer, 1989). Arousal refers to the extent to which one feels activated, and valence describes the range of one's well-being from pleasure to displeasure. Based on these two bipolar dimensions, Russell (1980) proposed the circumplex model of affect (see Figure 7). According to this framework, stress is characterized by heightened arousal and negative valence (Russell & Barrett, 1999). Although arousal and valence dimensions do not exhaust the multifaceted nature of emotion, researchers can use them to describe and identify common underlying characteristics. Importantly, arousal and valence can be assessed by either physiological or self-report measures (see detailed information in Section 3.3.2.3), although these two types of measures sometimes conflict (Levenson, 2014).

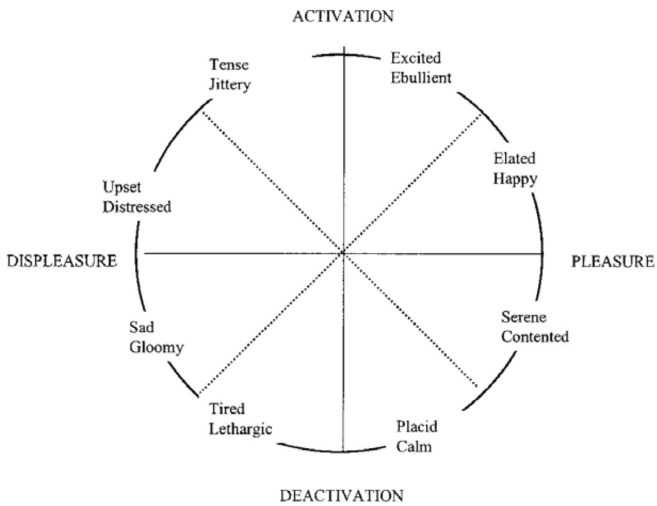


Figure 7: The circumplex model of affect can be used to define stress states as a specific combination of arousal (from activation to deactivation) and valence (from pleasure to displeasure; Russell & Barrett, 1999)). Image source: Sander and Scherer (2014)

Key findings about stress assessment

Stress can be considered a result of individual appraisal processes and leads to different psychological and physiological reactions in different people. Attempts to connect the various aspects involved in stress have resulted in theories that define a small set of core dimensions (Russell & Barrett, 1999; Watson & Tellegen, 1985; Thayer, 1989). In the present thesis, I rely on the circumplex model of affect (see Figure 7). Arousal describes the extent to which one feels activated, and valence describes the range of one's well-being from pleasure to displeasure. Both dimensions can be assessed using physiological and self-report measures. In this model, stress can be defined as negative valence and positive arousal.

2.7 STRESS AND SPATIAL LEARNING

Psychological research has demonstrated that many cognitive functions are sensitive to stress. For example, stress has been shown to impact attention (e.g., attentional scope, selective attention), memory (e.g., the acquisition, consolidation, and retrieval of memory), and learning (goal-directed or habit learning; Sandi, 2013). In this literature summary, I will focus on two stress-related effects that are of primary relevance for the present research: attentional narrowing and the impairment of WM functioning.

2.7.1 Attentional narrowing

Attentional narrowing is a term that has been used in different contexts. First, attention can be narrowed toward the arousing stimulus (e.g., information that is central to an emotional event) at the expense of less arousing stimuli (e.g., Loftus, Loftus, & Messo, 1987). Second, stress can narrow attention spatially toward central stimuli at the expense of peripheral stimuli. In this latter approach, researchers often place participants in a state of heightened arousal and assess their spatial learning performance for neutral stimuli (Brunyé, Mahoney, Augustyn, & Taylor, 2009). Following the metaphor of a spotlight (Posner, Snyder, & Davidson, 1980), researchers found that negative affective states can reduce accuracy and increase response time for detecting peripheral visual targets (Callaway & Dembo, 1958; Reeves & Bergum, 1972). Similarly, positive valence has been associated with an increase in the processing of spatially distant distractors (Rowe, Hirsh, & Anderson, 2007). While these experiments investigated the spatial extent of attentional focus on a 2D plane in figural spaces, recent research has expanded the zoom-lens metaphor of attentional narrowing to include 3D environmental spaces. For example, Gardony et al. (2011) demonstrated that high arousal states can influence the use of near and far landmarks for navigation in virtual reality. In their study, participants in low arousal states used distant landmarks (i.e., in the spatial periphery) more efficiently for navigation than participants in high arousal states (Gardony et al., 2011).

2.7.2 Working memory impairments

During stress, activation of the sympathetic nervous system (i.e., arousal) is accompanied by an engagement of the prefrontal dopamine system, which releases norepinephrine. High arousal and high doses of norepinephrine can lead to impairments of WM functioning (Arnsten & Li, 2005). Similarly, glucocorticoids exerted by the hypothalamic-pituitary-adrenal axis during episode of stress can impair the optimal functioning of WM (Oei, Everaerd, Elzinga, van Well, & Bermond, 2006). While prior research has observed that stress can either facilitate or impair WM in different contexts (Joëls, Pu, Wiegert, Oitzl, & Krugers, 2006), there are more consistent results for stress-induced WM impairments on more complex tasks that required users to actively maintain old information while constantly updating new information in memory (Lupien, Gillin, & Hauger, 1999; Oei et al., 2006). For example, stress impairments are often found when participants solve the n-back task (Owen, McMillan, Laird, & Bullmore, 2005). In this task, participants need to monitor sequences of briefly presented stimuli and have to respond under time constraints whether or not the currently presented stimulus is identical to the stimulus presented n trials before. The task requires the continuous monitoring, updating, and manipulating of stored information and is consequently assumed to challenge a number of key processes within WM (Owen et al., 2005). While WM impairments are detrimental for these kinds of tasks, other simpler tasks might not be affected. To date, prior navigation research has not considered the type of information that people can successfully encode during episodes of distress or high arousal (Thoresen et al., 2016; Gardony et al., 2011).

2.7.3 Effects of stress on spatial learning

Prior research has found mixed evidence for the relationship between stress and spatial learning. One study on stress and spatial knowledge acquisition exposed one group of participants to a loud, unpredictable noise (Evans et al., 1984) and assessed the effects of this noise on spatial learning. In this study, participants viewed videos of walks through urban environments with or without salient landmarks. To assess spatial learning performance, the researchers asked participants to place photos from the video walkthrough on a large piece of paper in their respective locations. Participants exposed to environments with salient landmarks performed significantly better than participants exposed to environments without salient landmarks, but the (seemingly stressful) noise manipulation eliminated any advantage provided by the landmarks (Evans et al., 1984). Unfortunately, the extent to which the observed effect is attributable to stress (as typically defined using physiological or self-report measures) is unclear.

In addition, Richardson and Tomasulo (2011) observed a negative effect of a stressful task on the speed with which participants performed a spatial memory task (but not their accuracy) after navigation through a virtual environment. One group of participants was first instructed to trace a figure viewed in a mirror, and another group of participants watched a nature video. Then, each of the participants was asked to learn the locations of target objects along different paths in a virtual environment. The researchers assessed spatial learning by "teleporting" participants to selected landmarks and asked them to point to other landmarks. Physiological and self-report measures were used to assess the stress level of the two experimental groups (Richardson & Tomasulo, 2011), but only self-report measures verified a difference between the groups.

In contrast, Duncko et al. (2007) demonstrated that exposing participants to a cold pressor procedure before navigation through a virtual environment can actually improve spatial learning. Participants performed a virtual reality version of the Morris water maze task in which they were asked to navigate towards a particular location as quickly as possible over a series of trials. The results revealed that participants exposed to the cold pressor procedure navigated towards the goal location with significantly smaller heading errors and fewer overall failures. Duncko et al. (2007) also verified physiological stress response in the cold pressor group as a significant increase in heart rate.

All previous studies that investigated the relationship between arousal (or stress) and spatial knowledge acquisition employed a seemingly stressful task before navigation rather than manipulating the navigation task to be more stressful itself. An alternative approach that is adopted in the present studies is to attempt to manipulate stress using time pressure or increased workload and measure arousal physiologically during the navigation task. Furthermore, prior research did not explore the role of WM when navigators acquire spatial knowledge under stress.

Key findings about stress and spatial learning

Stress has been associated with inattention to global landmarks and/or negative effects on WM functioning. This might in turn impair survey knowledge acquisition in environmental spaces because stress might reduce a navigator's ability to attend and encode spatial relations of landmarks in WM. However, prior research that investigated the effects of acute stress on spatial learning has not examined the mediating role of working memory during spatial knowledge acquisition. Specifically, the extent to which WM is required during spatial knowledge acquisition might depend on the type of spatial information being processed. The present work investigates local and global landmark learning under stress and considers the possible role of WM as a mediator between stress and learning environmental spaces. In doing so, the present thesis aims to elucidate the usefulness of attending to local or global landmarks for everyday navigation.

2.8 SUMMARY

Taken together, prior navigation research indicated that spatial learning might benefit from visual access to global landmarks (H. Li et al., 2016; Steck & Mallot, 2000). Similarly, research on memory for 2D figural spaces and vista spaces hints towards a potential advantage in the mental processing of spatial relations between simultaneously visible (global) landmarks over sequentially visible (local) landmarks in WM (e.g., Lecerf & De Ribaupierre, 2005). However, no prior research has directly compared the effectiveness of local and global landmark configurations for survey knowledge acquisition.

Furthermore, empirical findings from the stress literature have indicated an impairment of WM (Oei et al., 2006) and/or inattention to global landmarks (Gardony et al., 2011) with stress exposure. Thus, navigators ability to acquire survey knowledge may be impaired under such circumstances. However, prior evidence on the relation between stress and survey knowledge is mixed (Duncko et al., 2007; Richardson & Tomasulo, 2011; Evans et al., 1984) and the benefits of global landmarks for spatial learning remain an open question.

The present thesis aimed to close these gaps by examining navigators' abilities to acquire survey knowledge from attending to local or global landmark configurations in virtual cities with and without different stressful contexts (i.e., time pressure in Study 1 and high concurrent task load in Study 2). In the following chapter, I will describe the methodological approach that is employed in these experiments.

Chapter 3

METHODOLOGY

In this chapter, I will introduce the empirical methods that were employed for the present thesis. In Section 3.1, I will outline the scientific approach of using virtual reality (VR) as a research tool to investigate spatial cognition. Then, in Section 3.2, I will describe the experimental setup and the hardware and software that were used to run the experiments and to collect the data. In Section 3.3, I will give an overview of the designs of the two studies, specifying the experimental variables. Please find the operationalization of the research questions and detailed information about the conditions, procedures, and data analyses in the methods part of each study chapter.

3.1 VIRTUAL REALITY NAVIGATION

VR involves the use of computer generated simulations that provide users the opportunity to interact with environments that appear and feel similar to the real world (Kizony, Levin, Hughey, Perez, & Fung, 2010). The use of VR for investigating navigation and spatial cognition is well-established (Gillner & Mallot, 1998; Patrick Péruch & Wilson, 2004; Gardony et al., 2011; Richardson et al., 1999). For the present thesis, participants navigated through virtual environments. Navigation studies using VR allow researchers to design environments according to their needs and enable experimental manipulations that would not be possible or cost-efficient in the real world. For example, with VR, I could precisely operationalize the visibility of local and global landmarks and simultaneously control their perceptual properties (Section 2.4).

Although VR studies can provide insights into many aspects of navigation, these techniques have some limitations for forming a comprehensive understanding of the cognitive mechanisms involved during navigation. The most fundamental criticism of VR is the absence of bodily motion cues. In Section 2.1.2, I have discussed the manner in which motor, kinesthetic, and vestibular cues are used to mentally update one's bodily orientation in space. However, when using most VR techniques, participants do not physically walk in order to move the location of their virtual avatar. Navigation studies that visually simulate self-motion in the absence of any physical movement are restricted to visually-based spatial updating. Hence, researchers who rely on such VR techniques need to be cautious about drawing conclusions about real-world spatial cognition (Hegarty et al., 2006). For example, Waller, Loomis, and Haun (2004) found that navigators who had access to both visual and kinesthetic information during navigation showed reduced pointing error to learned landmarks along the traveled route compared to a group who watched videos of these walks. However, for the present research, this decrease in ecological validity from relying on VR was deemed acceptable in order to increase experimental control and internal validity (Loomis, Blascovich, & Beall, 1999).

In line with this reasoning, a variety of empirical findings support the general validity of VR experiments for studying spatial cognition. Specifically, much evidence supports the argument that spatial memory acquired from VR is fundamentally similar to that acquired in real environments (Richardson et al., 1999; Foreman et al., 2000; Bliss, Tidwell, & Guest, 1997; Gillner & Mallot, 1998, 1998). For example, humans show similar performance for navigation through real and virtual environments when judging spatial directions (Tlauka, 2007) or distances (Jansen-Osmann & Berendt, 2002) from memory. In addition, prior research suggested that the relative contribution of sensing body-based information for spatial updating might be small compared to the contribution of visual information. For example, visual cues alone (e.g., optic flow and/or landmark piloting during virtual navigation) can be sufficient for updating spatial positions and orientations (May, 2000; Kearns et al., 2002; Riecke et al., 2007).

3.1.1 Display size and field of view

One factor that may influence spatial learning in VR is display size and field of view (FOV), because FOV is often restricted in virtual compared to real environments. Indeed, smaller FOVs can increase users' cognitive demands for updating the body-to-space relationships (Hegarty et al., 2006; Riecke, Schulte-Pelkum, & Buelthoff, 2005). In addition, prior research has demonstrated that a large FOV can positively affect the accuracy of distance perception Kline and Witmer, 1996 and the detection of a visual target Arthur, 1996; Ragan et al., 2015. With a larger FOV, users might also be more inclined to orient naturally because they can, for example, move their heads to quickly scan larger areas of the environment. Therefore, the present thesis employed a three-wall immersive VR system with more than 200 angular degrees FOV.

3.1.2 Stereoscopic vision

Recent VR technology also allows for the simulation of binocular vision. Binocular vision results from the fact that humans have two separated, forward-facing eyes that receive two slightly different, but overlapping, images. In the brain, these images are unconsciously fused into a single three-dimensional image that (in combination with various monocular cues) provides accurate depth perception. Empirical evidence indicates that these binocular depth cues support humans in a variety of spatial tasks. For example, McIntire, Havig, and Geiselman (2014) comprehensively reviewed 160 publications and found that participants in only 25% of the reported studies did not benefit from the additional depth cues of stereoscopic displays. Of the 12 studies that involved virtual navigation, five (42%) demonstrated a clear positive effect of stereoscopic displays on navigation performance. Furthermore, 13 (52%) of the 25 studies that investigated memory and the understanding of complex spatial figures showed beneficial effects of stereoscopic images. In most cases, this research suggests that the binocular depth cues provided by stereoscopic displays can benefit users. Furthermore, no studies have reported impairments in spatial task performance due to stereoscopic compared to non-stereoscopic displays.

3.1.3 Simulator sickness

Visually induced self-motion might decrease a user's well-being by causing simulator sickness (Dichgans & Brandt, 1978). Simulator sickness often results from a conflict between multi-sensory inputs such as those resulting from simulated and physical movement of the user's body in space (Helland et al., 2016). Some of the most important symptoms of simulator sickness (i.e., those that appear in large proportions of the population) are dizziness, disorientation, nausea, and drowsiness (McIntire et al., 2014). Simulator sickness is a major obstacle for VR research because these symptoms might confound results, reduce statistical power, and/or cause participants to abort the experiment early. Test aborts might also introduce a bias in the sample because people who abort the experiment early might be systematically different than those who do not (e.g., in terms of stress response). Prior research has found relatively high abort rates of 17% due to simulator sickness (Brooks et al., 2010). To minimize sources of sickness in the CAVE setup, I implemented slow (3.8m/s) and steady (as opposed to changing) self-motion speed and rotation (Bubka, Bonato, Urmey, & Mycewicz, 2006; So, Lo, & Ho, 2001). Also, I excluded participants who are older than 36 years because older people tend to be more sensitive to simulator sickness than younger people Roenker, Cissell, Ball, Wadley, and Edwards (2003). I also assessed the self-reported severity of sickness symptoms for each participant of the present studies using the well-established Simulator Sickness Questionnaire (Kennedy, Lane, Berbaum, & Lilienthal, 1993), once before (pre-task) and once after (post-task) each session.

3.2 EXPERIMENTAL SETUP

In both of the present studies, the display of the virtual environments was rendered on a three-wall immersive VR system called the CAVE (i.e., Cave Automatic Virtual Environment). The CAVE is located in a room without windows in the Department of Geography at the University of Zurich. The CAVE has three screens located in front, to the left, and to the right of the participant. Each screen consists of a reflective canvas and is 312 cm wide by 195 cm tall. Images are front-projected onto each screen in stereo 3D with 1280x800 pixels at 120Hz frequency using ultra-short-throw projectors (NEC NP-U310W) that are mounted at the ceiling. The back-end rendering is provided by a single workstation (Boxx Apexx 4, Intel Core i74960x, 3.6 Ghz, 16 GB RAM, x64 processor) equipped with a NVIDIA Quadro K6000 graphics card (797 Mhz GPU clock, 12GB DDR5 memory with a bandwith of 288.4 GB/s) that has a theoretical pixel rate of 54 GPixel/s. The city environments were rendered at a constant frame rate of 60Hz. Figure 8 illustrates the experimental setup, including the CAVE, the desktop computer on which participants completed questionnaires, and the experimenter's workstation. For an observer sitting at the central position, the CAVE has a horizontal FOV of more than 200 degrees (see Section 3.1.1). The participant's viewpoint in the CAVE was offset 60 cm above the position of the shutter glasses worn by the participant. This offset compensated for the difference between participants' sitting height and their hypothetical walking height in the virtual environment.

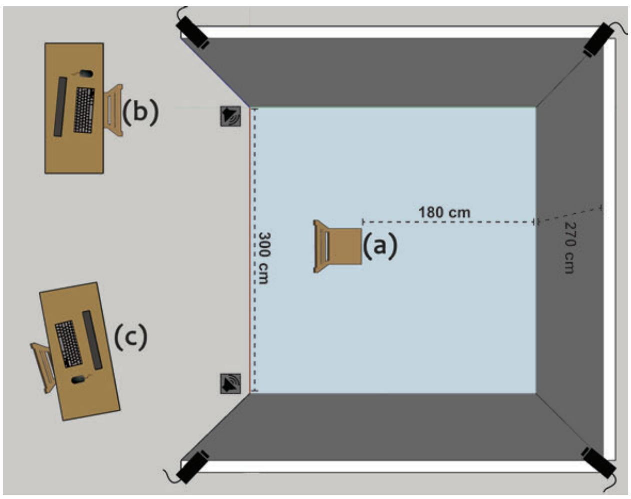


Figure 8: The illustration shows the CAVE setup including (a) the participants' sitting position when navigating a virtual world, (b) their workstation while completing questionnaires or tests, and (c) the experimenter's workstation. Furthermore, there were two loud speakers located at the back corners of the CAVE and four optical sensors that were mounted to the top corners of the display.

For both studies, virtual environments were displayed in stereoscopic 3D, simulating binocular vision (see Section 3.1.2). To render viewpoint-corrected images for each of the two eyes, participants' head positions and orientations were continuously tracked using four optical sensors that were mounted to the top corners of the display screens (see Figure 8). The tracking targets were attached to the 3D glasses worn by participants. Shutter glasses technology controlled the timing between the projections on the CAVE screens and the transparency of each lens on the glasses to simulate binocular vision. As a result, each eye received an image from a slightly different perspective, corresponding to the typical separation between a viewer's eyes.

The experimental tasks were written in Python and rendered with Vizard 5.6 (WorldViz, Santa Barbara, CA, USA; worldviz.com). The 3D environments were designed using City Engine 2014 (Esri, CA, USA; esri.com/software/cityengine). Physiological data acquisition and facial electromyography (fEMG) data analysis was conducted using AcqKnowledge 4.4 (Biopac Systems Inc.). Electrodermal activity (EDA) data was analyzed using LedaLab, a Matlab-based software (Benedek & Kaernbach, 2010). Using network data transfer, physiological recordings from AcqKnowledge were synchronized in real-time with the behavioral data (e.g., navigation trajectories) generated by the Vizard script.

3.3 METHODOLOGICAL OVERVIEW OF STUDIES

Table 1 lists the experimental variables of both experiments. The remainder of the section is structured according to these variables.

3.3.1 Independent variables

Two laboratory VR studies were conducted in the CAVE. In both studies, participants had to navigate virtual cities and remember the relative locations of a predefined set of highlighted local or global landmarks (factor: landmark) in situations with and without stress (factor: stress). In Study I, in addition to the local and global landmark conditions (LOC | GLO), I included a condition (attentional narrowing) to understand the effect of stress on participants' spontaneous attention to global landmarks to support learning (Section 2.7.1). In the two studies, I employed different stress induction approaches (i.e., time pressure and workload). This chapter gives some detail regarding the general approach to induce and assess stress in both studies (see Section 3.3.1.2). However, this chapter does not cover every detail about these analysis of these measures and their respective application in the VR. Furthermore, for the sake of readability, some measures will be described only in the study sections. For example, participants performed spatial ability tests before the study (i.e., perspective-taking and WM capacity). These tasks will be introduced in the study sections (Chapter 4 and Chapter 5).

Table 1: The table shows the independent and dependent variables of Study I and Study II.

	Independent Variables		
	Landmark Condition	Stress Condition	Spatial Abilities
EXP I	LOC | GLO | AN	time pressure: with | without	perspective taking test
EXP II	LOC | GLO	spatial tapping: with | without	WM capacity
	Dependent Variables		
	Spatial Knowledge	Pointing Confidence	Stress Measures
EXP I	pointing accuracy (JRD)	continuous rating scale	EDA fEMG SSSQ
EXP II	pointing accuracy (JRD)	continuous rating scale	EDA SSSQ

LOC = local landmark condition, GLO = global landmark condition, AN = Attentional narrowing condition, JRD = Judgment of relative direction, WM = Working memory, SSSQ = Short Stress State Questionnaire, EDA = Electro Dermal Activity, fEMG = facial Electromyography

3.3.1.1 Operationalization of local and global landmarks

Target landmarks were buildings selected from the virtual cities that participants were explicitly asked to remember in terms of their identities and spatial locations. Target landmarks were highlighted in different colors in the virtual environment. The present thesis defined local and global target landmarks based on their visibility properties from the predefined experimental route. Local landmarks were low-rise buildings that were located along the route. There was always at least one turn between local target landmarks so that a participant could not see more than one local target landmark at a time (i.e., requiring sequential encoding). Global target landmarks were high-rise buildings, and participants could see more than one of them at a time (i.e., allowing simultaneous encoding).

Figure 9 illustrates the differences in visual access to the target landmarks in the local and global landmark conditions. The target landmarks and the experimental route are depicted in black. The colors encode which parts of the environment have visual access to none (red), one (green), or more than one (yellow) target landmarks. In the local landmark condition, participants could not see the facades of more than one target landmark at a time. In the global landmark condition, the yellow area covers the entire route and demonstrates that at least two target landmarks were visible from each part of the route.

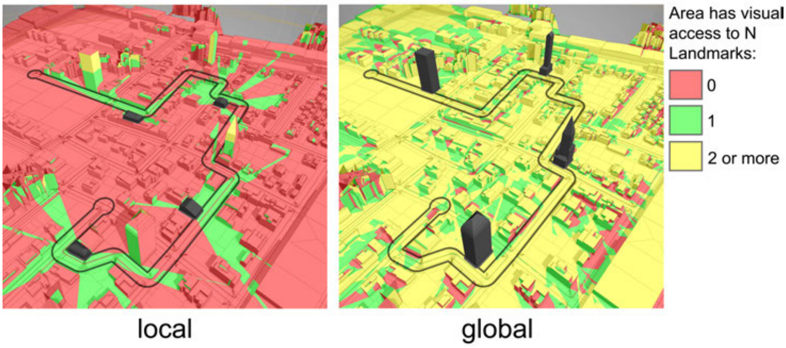


Figure 9: Visibility analysis of local and global landmarks. The 3D models represent a city environment that was used in Experiment II.

Notably, due to the fact that participants navigate city-scale environments from ground-level perspective, the present operationalization of global landmarks is not precisely the same as in prior studies that investigated sequential and simultaneous encoding in room-sized spaces (e.g., Meilinger, Strickrodt, & Bülthoff, 2016; Ruotolo et al., 2012). In contrast to these studies, participants in the present study cannot immediately oversee the locations of all objects from a birds-eye perspective, like in a map. Rather simultaneous encoding is defined here that participants can often see multiple global landmarks on the horizon. However, the exact location needs to be inferred from an egocentric perspective.

3.3.1.2 Operationalization of stress

To understand the mental encoding of landmarks in stressful situations, the present thesis relies on two variants of task-induced stress. Task-induced stress can be defined as a stressful experience that is induced by the high cognitive demands of a given task (Matthews et al., 2013).

First, cognitive demands can be increased using time pressure (Szalma et al., 2004). In Study I, I employed such an approach by placing one group of participants under time pressure. The advantage of time pressure as a manipulation of stress is high ecological validity because time pressure is a typical, everyday experience during navigation. However, according to the literature, the effects of stressors on cognition are manifold and might strongly differ between individuals and tasks (Section 2.7). Specifically, stressors lead to different affective responses across different individuals (Sandi, 2013) and thus may disrupt working memory functioning only in a subset of these individuals. Given that the theoretical link between spatial learning impairments and stress relies on the impairment of WM (Section 2.7.2), this approach can lead to high variance in the aggregated stress data. To account for this possibility, I collected several measures of stress (i.e., self-reported and physiological) and individual spatial abilities and navigation strategies.

In Study II, I induce stress by increasing the concurrent task demands of one group of participants. I use this approach to investigate the effects of WM impairments that typically occur during stressful episodes (see Section 2.7.2) on spatial learning. Prior research has successfully used concurrent task performance to induce storage and processing impairments in WM (Baddeley & Hitch, 1974; Lindberg & Gärling, 1981). The disadvantage of this method is that the interpretation of the results as "stress-effects" relies on the assumed negative relation between psychophysiological stress and WM impairments (e.g., Arnsten & Li, 2005).

3.3.2 Dependent variables

3.3.2.1 Judgments of relative direction

In recent decades, researchers in spatial cognition have advanced several behavioral techniques for studying the characteristics and accuracy of human spatial memory in the laboratory. Depending on the type of spatial knowledge being studied, different measurement methods need to be applied. In other words, the different types of mental spatial representations introduced so far allow a person to perform different spatial tasks. For example, route knowledge may allow navigators to re-walk a familiar route. Tasks that are used to measure survey knowledge include short-cutting (Foo et al., 2005), sketch mapping (Zhong & Kozhevnikov, 2016), landmark placement tasks (Meilinger, Frankenstein, Simon, Bülthoff, & Bresciani, 2016), and egocentric and allocentric pointing tasks (Wen et al., 2013). Recently, there is increasing evidence that taking novel short-cuts can be based on non-metric mental representations (Bennett, 1996; Warren et al., 2017). In addition, sketch mapping might be an inappropriate way of assessing survey knowledge because it often involves unique skills such as drawing that introduce noise in the data (Chrastil & Warren, 2013).

Conversely, it has been shown that the judgment of relative direction task (JRD task) reliably measures the accuracy of individuals' survey knowledge (Zhang et al., 2014; Huffman & Ekstrom, 2018). Judging the relative directions between objects from memory involves mentally accessing the spatial relationships among the objects' locations and attempting to accurately determine their relative direction (Shelton & McNamara, 2004). For example, for each JRD task, participants may be asked "imagine you are standing at landmark A, facing landmark B, in which direction is landmark C?" In the JRD task, participants need to recall spatial relations completely from memory. In contrast, during egocentric pointing tasks, the environment often remains visually present and participants judge directions from displayed locations in the environment (although the pointing targets may be removed) (Waller & Hodgson, 2006).

Following each navigation trial of each study, participants were tested on their spatial memory using JRD tasks in order to assess landmark-based survey knowledge. In a single JRD task, participants are asked to recall the locations and directions of landmarks relative to each other, irrespective of their current egocentric position and heading. Therefore, participants saw three different landmarks that were presented on the front screen of the CAVE and rotated around their vertical axis. Rotation was introduced because the façades of buildings are recognized better from an experienced view than from an unfamiliar view (Christou & Bülthoff, 1999), and it was not known exactly from what perspective the landmarks were viewed during navigation. The instructions asked participants to imagine standing at a first landmark, facing a second landmark, and pointing to a third landmark.

To judge directions, participants were presented with a screen that showed a white cross on a black background in the center of the front screen of the CAVE (see Figure 10. The white cross represented the reference direction (2nd landmark), whereas the black square, marked on the floor in the center of the cave, represented the reference location (1st landmark) for the JRD. To complete the JRD, participants held the pointing device in the estimated direction of the third landmark, and confirmed their decision by pressing a button on the pointing device. The orientation of the pointing device was tracked by an inertial measurement unit and the four optical sensors.

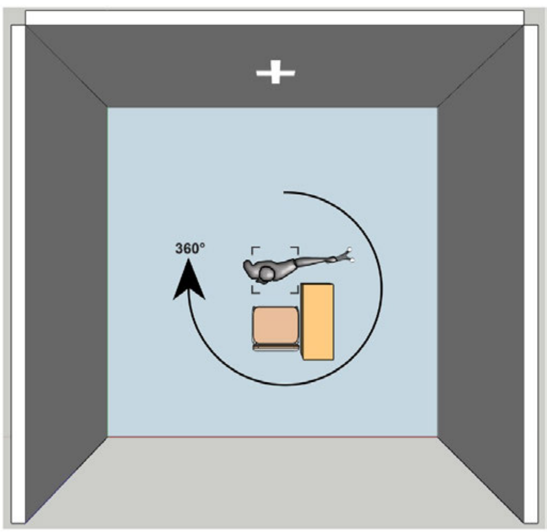


Figure 10: The CAVE illustrated from a top-down perspective. During the JRD task, participants stood upright in the middle of the CAVE.

3.3.2.2 Confidence ratings

Participants were also asked to indicate their confidence for each individual JRD task. Prior research has reported a relationship between participants' JRD accuracy and their self-reported confidence regarding JRD performance (Huffman & Ekstrom, 2018; Stevens & Carlson, 2016). This relationship indicates that participants can consciously access their mental spatial representations of an environment. Hence, peoples self-reported confidence might be used as an additional indicator of the accuracy of their mental representations. However, different aspects of the environment being learned might influence the way in which we perceive the quality of our spatial knowledge. For example, it has been shown that self-reported confidence increases with repeated exposure to an environment or landmark in question (Huffman & Ekstrom, 2018; Stevens & Carlson, 2016). This finding suggests that JRDs for global landmarks should lead to higher self-reported confidence ratings than JRDs for local landmarks because they are visible more frequently.

Participants' confidence ratings were collected after each pointing trial using the joystick of the pointing device. On the screen, participants rate their confidence on a continuous scale with "I am very confident" on the right side, and "I have guessed" on the left side. Understanding the relations between participants' actual memory accuracy and their confidence ratings might help us understand the potential pitfalls of local or global landmarks as learning support.

3.3.2.3 Stress measures

To my knowledge, all previous studies that investigated the relationship between arousal (or stress) and spatial learning employed a seemingly stressful task before navigation rather than manipulating the navigation task to be more stressful itself (see Section 2.7). An alternative approach that was adopted for the present studies is to manipulate task-related factors such as time pressure or concurrent task load and measure physiological arousal during the navigation task. This approach may help elucidate the cognitive mechanisms underlying a possible relationship between stress and spatial learning. To measure individuals' stress responses that are evoked due to these different task-related factors, I employed a variety of methods.

3.3.2.4 Physiological assessment of arousal

From a physiological perspective, stress manifests as changes in eccrine sweating that occur over a short amount of time, is related to activation/arousal of the sympathetic nervous system (Figner & Murphy, 2011), and can be measured using electrodermal activity (EDA) (Boucsein, 2012). Eccrine sweating changes the measurable conductivity of the skin (measured in microsiemens) and has been successfully used in many areas of research as an indicator of stress (Figner & Murphy, 2011). Notably, skin conductance can be caused by several different phenomena, including physical effort (e.g., body movements), sensory stimulation (e.g., temperature), but also serves as a proxy for psychological mechanisms such as cognitive load and arousal. To use EDA as an indicator for psychological phenomena, a laboratory setup is crucial for controlling possible confounds. In addition, researchers should record individual reference measurements (i.e., off task) to account for individual differences. In contrast, ambulatory recording is typically noisy, and artifacts in the signal can easily be mistaken for a physiological response during analysis (but see Taylor et al., 2015).

The EDA signal can be decomposed into phasic and tonic components that represent short-term (skin conductance response or SCR) and long-term (skin conductance level or SCL) changes of activation in the sympathetic nervous system. Phasic changes in the signal appear as short-term waves superimposed on the SCL (Boucsein, 2012). Traditionally, researchers used so-called event-related skin conductance responses (ER-SCR) that are short-term changes of the signal in response to an event or experimental stimulus. Responses that occur within a predefined response window (typically 1-3 sec) are defined as ER-SCRs. Responses that occur before or after that window are defined as non-specific skin conductance responses (NS-SCR) and are commonly considered as unrelated to momentary experimental manipulations. In case the experimental design does not incorporate event-like arousing stimuli, phasic responses can be generally defined as non-specific. Recent evidence has shown that the analysis of the frequency of NS-SCRs can be used as a tonic EDA measure and may reflect the general presence of an arousing and negatively tuned cognitive activity (Boucsein, 2012).

However, identifying SCRs relies on the detection of local maxima in the time-series and considering the stimulus onset as a baseline to compute the amplitude. This identification technique can be imprecise in the case of closely superposing SCRs because the shape of an SCR could be altered by the tail of the preceding SCR (Benedek & Kaernbach, 2010). Findings from physiological studies have shown that an SCR is preceded by discrete bursts of the sudomotor nerves that control the sweat glands (Nishiyama, Sugenoya, Matsumoto, Iwase, & Mano, 2001). To reliably assess SCR amplitude, some methods account for this this sudomotor activity quantitatively using a method of deconvolution. In the present thesis, I will use such a deconvolution method (Benedek & Kaernbach, 2010) that back-propagates the raw signal to sudomotor nerve activity and subsequently uses these data to compute the tonic (SCL) and phasic (SCR) components of the EDA signal. To analyze stress levels during VR navigation with varying time spans, I will rely on time-normalized values of the tonic SCL and the non-specific skin conductance responses (NS-SCR).

3.3.2.5 Facial expressions can indicate valence

Positive and negative valence can be inferred from changes in facial expressions that have been related to emotional states (Read, 2017). For example, negative valence has been associated to inactivity over zygomaticus major, a muscle that moves the corners of the mouth into a smile, and activity of the corrugator supercilii, a muscle that draws the brow down into a frown (Larsen, Norris, & Cacioppo, 2003). Such muscle contractions generate electrical potentials that can be measured at the skin surface (i.e., facial electromyography or fEMG; A. J. Fridlund & Izard, 1983). Using electrical potentials, fEMG allows one to detect and quantify affective reactions to particular stimuli (Read, 2017).

The advantages of behavioral (fEMG) or physiological measures (EDA) are that they can be assessed continuously and noninvasively while participants perform a particular task. Both measures provide a measure of emotion that may be more reliable than participants' self-reports.

3.3.2.6 Short stress state questionnaire

The Short Stress State Questionnaire (SSSQ; Helton, 2004)) is a self-report measure that assesses how individuals feel while experiencing a given task or event. The SSSQ is a shorter version of the Dundee Stress State Questionnaire (Matthews et al., 2013). The questionnaire differentiates between three underlying aspects of the stress response: distress, task engagement, and worry (Matthews et al., 1999). Distress (high arousal and negative valence) is a psychological state that binds together energetic arousal and negative valence (Matthews et al., 2013). However, distress also involves nervous and negative feelings that emerge from appraisals of high workload and high task demands(Matthews et al., 1999). High distress levels have been associated with poorer WM functioning (Matthews & Campbell, 2010). The key drivers of the distress response are high task workload/cognitive load and time pressure (Matthews et al., 2002; Hockey, 1997). In contrast, task engagement is a mental state of high arousal and positive valence and results from the perception of the task to be challenging and interesting (Matthews et al., 1999). In addition, worry is defined as self-focused attention and the tendency to have intrusive thoughts. Increasing levels of worry indicate that an individual may be more inclined to allocate attention to some aspects of self-evaluation (Matthews et al., 2002). Concerning the relation between self-reported stress states and working memory impairment, (Matthews & Campbell, 2010) demonstrated consistent positive relation between higher distress ratings and poorer working memory performance.

Chapter 4

STUDY I

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Among other aspects of everyday navigation, stress might occur when we are struggling with time pressure (Wahlström et al., 2002). Psychological stress and high arousal have been associated with inattention to global landmarks and negative effects on working memory functioning (Section 2.7). Decreased working memory functioning may in turn impair survey knowledge acquisition for environmental spaces by reducing the navigator's ability to encode the spatial relations among landmarks into working memory (Section 2.6). There is also evidence from studies of spatial learning in figural and vista spaces that indicates that spatial information that is presented simultaneously (rather than sequentially) is easier to encode and represent in working memory (Section 2.3.3). Thus, global landmarks might be especially helpful for learning in stressful situations. However, prior research has not addressed the link between stress and the difference between sequentially visible (local) and simultaneously visible (global) landmarks for learning larger environments such as cities. Learning a configuration of landmarks while navigating larger environments should strongly rely on working memory resources because spatial information has to be mentally integrated over considerable amounts of time and from multiple perspectives. Therefore, the present study examined survey knowledge acquisition of local and global landmark configurations in a virtual reality study in which participants were asked to navigate cities either with or without time pressure.

4.1 RESEARCH QUESTIONS

In Study I, I will investigate the following research questions defined in Chapter 1. Notably, Study I investigates the effects of stress on survey knowledge acquisition from local and global landmarks using a time pressure manipulation.

1. How accurate is the acquisition of survey knowledge from local and global landmarks?

2. How does time pressure interfere with successful survey knowledge acquisition?

a) Is survey knowledge acquisition under time pressure more accurate from global landmarks than from local landmarks?

b) Does time pressure reduce the accuracy of survey knowledge acquisition from global landmarks via attentional narrowing?

3. What is the role of perspective taking ability during survey knowledge acquisition from local and global landmarks under stress?

4.2 METHODS

4.2.1 Participants

The study was conducted in German. Participants were recruited via two local online advertising services in Zurich. Specifically, I used the psychology recruitment server from the University of Zurich (www.psychologie.uzh.ch/probandenserver/) and the online market place for University of Zurich alumni (www.marktplatz.uzhalumni.ch/). Fifty-three people between the ages of 18 and 36 participated in the study for monetary compensation. Forty-eight of these participants completed all of the experimental tasks (Mage = 25.8 years, SDage = 6.2, 24 male). Five participants aborted the study because of slight nausea.

4.2.2 Ethics statement

All of the procedures performed in this study were performed in accordance with the ethical standards of the Swiss Psychological Society and the American Psychological Association.

4.2.3 Materials

Participants navigated through virtual cities at 3.8m/sec using a wireless one-handed joystick device (i.e., WorldViz Wand) and sitting in the CAVE (Section 3.2). To prevent the emergence of motion sickness, I tested virtual navigation with two participants in a pretest to study I. I found that too low (<1 sec) and too high (>2 sec) amounts of translation acceleration was perceived as unpleasant. Translation acceleration can be described as the time until one reaches maximum speed. Participants described a values between 1 and 2 seconds until reaching maximum speed as "natural". Consequently, I took 1.5 seconds as fixed acceleration value. Physiological measures were recorded with transmitter modules (i.e., BioNomadixx) attached to the participant's wrist for EDA and their head for facial EMG. These modules were wirelessly connected to the MP150 stationary acquisition unit (Biopac System Inc., GA, USA; https://www.biopac.com) via a local area network. At the participant's hand and face, 15 cm electrode leads connected each transmitter module to 24 mm disposable hydrogel electrodes (Ag-AgCl sensors).

4.2.3.1 Virtual Environments

In total, I created nine environments that combined three city models with three landmark sets. Each of the three city models had an area between 0.4 km^2 and 0.8 km^2. Building models consisted of low-rise buildings with heights between 5 m and 15 m. The street networks contained intersections with crossing angles between 65° and 115°, and the distances between intersections were between 20 m and 140 m. The sidewalk widths of all streets were constant at 3.5 m. Street widths were either 3.5 m, 7 m, or 10.5 m. There were no slopes, hills, or mountains inside or outside of the city area. Each city's route consisted of six turns (three left and three right turns). Figure 11 represents the street networks and the routes of each city.

Landmark sets were added to each city model with additional low-rise buildings (5 m to 15 m) located along the route (i.e., local landmarks) and/or high-rise buildings (80 m to 100 m) located in the distance (i.e., global landmarks). Local landmarks were restricted in visibility, and participants could not view more than one at a time. In contrast, global landmarks were visible from multiple locations along the route, and participants could often view more than one at a time. Figure 12 includes a screenshot of each of the three landmark sets within one of the three cities. In the local (without global) landmark condition, four local landmarks were added and highlighted. In the global (without local) landmark condition, four global landmarks were added and highlighted. In the local (with global) landmark condition, four local and two global landmarks were added, but only local landmarks were highlighted. I added only two global landmarks in the local (with global) landmark condition so that each individual landmark was more salient. Highlighted landmarks had distinct and fully saturated colors and unique geometry. In contrast, all other buildings had photo-realistic city textures with low color intensity.

4.2.3.2 Navigation Aid

During navigation through the VR, participants could display a navigation aid that contained the route to the destination on top of a planimetric 2D map. This map was displayed on the front screen of the CAVE and included a 0.071 km^2 section of the city (at the scale of 1:106) centered at the location of the user. The map showed the street network, the highlighted route, and the location of the user in the virtual environment (Figure 13). Buildings/landmarks were not displayed on the map. Map information was oriented track-up. When the navigation aid was displayed, the side screens turned white, and movement through the virtual environment was

Figure 11: The street network of each virtual city from a top-down perspective. The white lines represent streets. The blue lines depict the predefined route for each city. "S" represents the starting point of each route, and "E" represents the end point. The black dashed lines represent the accessible area within each environment. Participants entered the virtual city along the path indicated by the black arrow.

Figure 12: Screenshots representing the three landmark conditions. (a) In the local (without global) landmark condition, only local landmarks were added and highlighted. (b) In the global (without local) landmark condition, only global landmarks were added and highlighted. (c) In the local (with global) landmark condition, both local and global landmarks were added, but only local landmarks were highlighted. The key comparisons across these conditions are between (a) and (b), assessing the accuracy of acquiring local and global landmark knowledge, and between (a) and (c), assessing the impact of global landmark presence on the accuracy of acquiring local landmark knowledge.

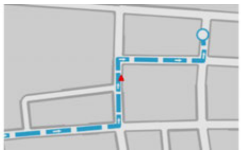

Figure 13: Screenshot of the track-up navigation aid. The red triangle indicated the location of the participant in the virtual city. On top of the blue route, white arrows indicated the correct direction along the route to reach the destination (blue circle).

disabled. In general, these features were inspired by contemporary mobile map designs and aimed to facilitate route-following while hindering landmark and survey learning directly from the map itself (e.g. Hermann, Bieber, & Duesterhoeft, 2003).

4.2.3.3 Questionnaires and Spatial Orientation Test

I administered four types of questionnaires (see Section A.1). First, orientation strategies were assessed with the Fragebogen Räumliche Strategien (FRS) questionnaire (Münzer & Hölscher, 2011). The FRS questionnaire focuses on the extent to which individuals rely on landmark-, route-, or survey-based strategies. Second, I administered a shortened version of the gaming questionnaire (items 1,2,3,5) originally developed by (Terlecki & Newcombe, 2005). This questionnaire focuses on participants' gaming experience. Third, simulator sickness was assessed using the Simulator Sickness Questionnaire (SSQ) developed by Kennedy et al. (1993). For the SSQ, participants rated 16 symptoms on a 4-point scale from absent to severe that were then used to generate scores for three simulator sickness subscales (i.e., nausea, disorientation, and oculomotor). Fourth, self-report measures of distress, engagement, and worry were assessed with the Short Stress State Questionnaire (SSSQ; Helton, 2004). Based on the testing platform hypothesis (Šašinka, Morong, & Stachoň, 2017), I also administered an online version of the spatial orientation test from Hegarty and Waller (2004).

4.2.3.4 JRD task

To assess survey knowledge, I employed the CAVE version of the JRD task Section 3.3.2.1. In the local (without global) and global (without local) landmark conditions, 12 out of 24 permutations were randomly chosen. From all 24 possible permutations, landmark triples that resulted in a symmetric angle (e.g., -60° and 60°) were paired, and only one triple of each pair was randomly chosen for the task. For example, instead of standing at A, facing B, and poining to C (ABC) and also standing at A, facing C, and poining to B (ACB), only one of the two trials was randomly selected. Overall, this resulted in participants performing 12 JRD trials per landmark condition. Only for the local (with global) condition, eight additional triples were randomly chosen. In these additional trials, participants were asked to imagine standing at a local landmark, facing a second local landmark, and pointing to a third global landmark.

4.2.4 Procedure

Participants were tested individually. Before the experiment, participants completed an online questionnaire on demographics (i.e., age, gender, and handedness), the gaming questionnaire, and the FRS questionnaire. After arriving at the laboratory, participants received a standardized overview of the upcoming experimental tasks that was read aloud by the experimenter. Figure 14 shows a similar, but more detailed overview. Then, participants provided informed consent and completed the spatial orientation test (Hegarty & Waller, 2004) on a computer screen. Subsequently, the experimenter attached the electrodes to the participants' fingers (EDA) and face (fEMG). EDA electrodes were placed at the medial phalanges of participants' index and middle fingers (Figner & Murphy, 2011), and fEMG electrodes were placed at the cheek (over the zygomaticus major), between and above the eyebrows (over the corrugator supercilii; Alan J. Fridlund and Cacioppo, 1986), and on the upper forehead as a reference electrode (Van Boxtel, 2010). At the EDA electrode sites, a light abrasive skin treatment was applied to lower skin impedance and moisten the underlying skin (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). For improving the fEMG signal, the fEMG electrode sites were cleaned with a mild alcohol wipe. Once the electrodes were attached and calibrated, the experimenter verified electrode impedance and checked their functionality. Then, participants rested for two minutes to ensure the hydration of the skin by the gel. After that, participants watched a two-minute nature video projected on the front screen of the CAVE. Physiological data was recorded during this nature video to later account for individual differences in physiological reactivity to acute stressors (Ulrich, 1981). Afterwards, participants read written instructions about the upcoming tasks, and the experimenter led the participants into the CAVE where participants sat on a chair and put on the 3D shutter glasses. Participants were familiarized with the experimental tasks and the apparatus in a training phase. During this phase, the experimenter led participants through all components of an experimental trial (e.g., navigation, map use, and the JRD task). I designed an extra city specifically for this training trial.

After the participant had no further open questions, the experimenter started the main experiment. The main experiment consisted of three blocks. Each experimental block consisted of a train ride, a navigation task, and a JRD task. During the train ride, participants were sitting in a virtual train waiting to arrive at the navigation destination. The train ride was intended to increase

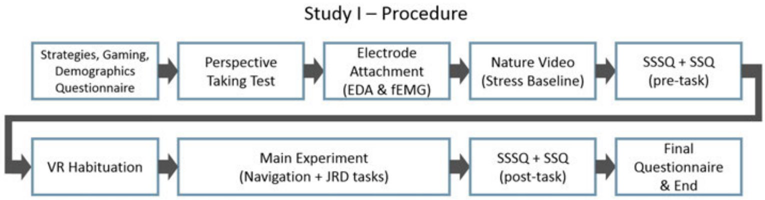

Figure 14: The procedure of Study I visualized as a flow chart. EDA= Electro dermal activity, SSSQ= Short stress state questionnaire, SSQ= Simulator sickness questionnaire.

the believability of the navigation task (Freeman, Lessiter, Pugh, & Keogh, 2005a), which can enhance users' emotional responses to the displayed content (Riva, Waterworth, & Waterworth, 2004). After a 30-second train ride, the participant's viewpoint was automatically moved out of the virtual train into the starting location of the navigation task. In the navigation task, participants were instructed to follow a predefined route as quickly as possible, and to memorize the relative locations of the highlighted landmarks as accurately as possible. The number of highlighted landmarks was unknown to the participants. Participants were explicitly instructed not to prioritize one of these two tasks. Participants were also asked not to leave the route marked on the navigation aid. When a participant left the route accidentally, a message appeared on the front screen asking them to return to the marked route at the location they left the route. Participants finished the navigation task when they arrived at the destination. Participants' survey knowledge was then assessed using JRDs. Participants completed 12 (or 20) JRDs (depending on the landmark condition they were assigned to). After each JRD measurement, participants indicated their pointing confidence on a continuous rating scale between "I am very confident" on the right site, and "I have guessed" on the left site. Pointing accuracy and confidence were both recorded automatically by the system. Before and after the main experiment, participants were asked to complete the SSQ (Kennedy et al., 1993) and the SSSQ (Helton, 2004), indicating their mental states immediately before the main experiment started and regarding the last minute of the main experiment.

4.2.5 Hypotheses

1. The acquisition of survey knowledge is more accurate from global than from local landmarks.
2. Time pressure disrupts the mental integration of landmarks in a survey representation via working memory.
   a) Time pressure disrupts the mental integration of local landmarks (sequentially encoded) in a survey represen-

tation more strongly than the mental integration of global landmarks (simultaneously encoded). Hence, survey knowledge acquisition under time pressure is more accurate from global landmarks than from local landmarks.

   b) Time pressure also reduces the accuracy of survey knowledge from global landmark configurations via attentional narrowing.

3. Perspective taking abilities are more relevant for the integration of local than for global landmark configurations.

4.2.6 Design & Analysis

4.2.6.1 Design

This study included two independent variables in a 2 (time pressure / no time pressure) x 3 (local without global landmarks / global without local landmarks / local with global landmarks) mixed factorial design. Participants were randomly assigned to either the time pressure or no time pressure group (i.e., between-subjects) but completed all three landmark conditions (within-subjects in a counterbalanced order). Dependent variables included questionnaire data, the survey knowledge measure (i.e., JRD accuracy), the confidence measure (i.e., how certain are participants with each directional judgment), and physiological measures (i.e., EDA and fEMG).

4.2.6.2 Time pressure manipulation

Participants in both the time pressure and no time pressure conditions were asked to reach the destination as quickly as possible and learn as accurately as possible. In the time pressure group, two scores were introduced. First, I introduced a learning score that was not displayed, although participants were instructed that it was related to JRD performance. Second, participant's time score began at 100 points and decreased by 1 point every 10 seconds during navigation. After losing every 10 points, the current time score was highlighted, and a beep sound was played. The deduction of points began during the train ride when participants could not yet act to ameliorate the situation. Time pressure was also emphasized with an audio announcement regarding the delay of the train and a clock ticking sound that was played constantly in the background. This audio announcement began with the well-known jingle of the Swiss railway company. Participants in the time pressure group were told before the study that their monetary compensation would depend on both scores and varied between 10 CHF and 20 CHF. The framing of the incentive was negative, so participants began with 25 CHF and could lose between 5 CHF and 15 CHF. In the no time pressure group, participants had no performance scores, and the endowment was fixed at 20 CHF.

4.2.6.3 Survey knowledge measures

Survey knowledge was assessed as the accuracy of JRDs (Section 3.3.2.1). JRD accuracy was defined as the absolute angular difference between the estimated direction and the actual direction of a target relative to the reference landmarks. Angular errors could vary between 0°(very accurate) and 180°(very inaccurate). An understanding of the chance level performance improves interpretation of the data. It is commonly expected that chance performance in the JRD task is stable at 90 degrees (Waller & Hodgson, 2006; Zhang et al., 2014). However, chance level performance can deviate from 90 degree (Huffman & Ekstrom, 2018). To determine the level of chance performance in the present data, I examined angular errors of trials where participants indicated the lowest confidence rating "I have guessed" (Huffman & Ekstrom, 2018). The distribution of these errors can be expected to indicate JRD performance at chance level. Using one-sample t-tests, I tested whether guessing performance differed from the chance level that was determined using the confidence ratings.

The data were analyzed in R version 3.5.2 (R Core Team, 2018). First, we ran an omnibus test using a mixed 2 (between) x 3 (within) ANOVA. If the assumption of homogeneity was not met, absolute angular errors were submitted to an aligned-rank transformed non-parametric analysis of variance (R package ARTool version 0.10.6; Wobbrock, Findlater, Gergle, & Higgins, 2011). The ART ANOVA allows accurate treatment of nonparametric data by aligning the dependent variable with respect to each main and interaction effect before converting the data to ranks (Wobbrock et al., 2011). After the Omnibus analysis, ANOVAs were conducted on two different data subsets which contained observations from condition a (local without global) and b (global without local) or observations from condition a (local without global) and c (local with global). The former comparison (a versus b) addresses the accuracy of acquiring survey knowledge from local and global landmark configurations. The latter comparison (a versus c) addresses the impact of global landmark presence on the accuracy of acquiring survey knowledge from local landmark configurations.

4.2.6.4 Psychophysiological measures

The data obtained from both EDA and fEMG signals were extracted at 1000 Hz. The experimental script automatically logged predefined events (e.g., the start and end of a navigation trial) in the physiological recordings. EDA data was then downsampled to 10 Hz. This procedure attenuates noise and smooths the data. There were no post-hoc filters applied to the EDA signal. By means of a continuous decomposition analysis (CDA), I decomposed EDA data into continuous tonic and phasic activity (Section 3.3.2.4). For the present study, I assessed arousal level over longer time spans from approximately three to six minutes (i.e., the duration of the navigation task). High arousal states were operationalized as a change in the tonic component of EDA (i.e., skin conductance level or SCL) or as an increase of non-specific skin conductance responses per minute (NS-SCRs/min). Hence, statistical analysis of this EDA data was based on computing intra-individual changes for both mean tonic SCL and mean NS-SCRs per minute. Difference values were computed by subtracting the individual mean values of the navigation conditions from the baseline condition. Baseline normalized mean scores for EDA were then submitted to independent-samples t-tests (two-tailed) in order to test if time pressure condition increased arousal.

A FIR bandpass filter (28Hz – 500Hz) was applied to the raw fEMG signal using a Blackman window. The frequency cut-offs are based on the predominant frequency range of fEMG signals (Van Boxtel, 2010). Then, I computed the root-mean-square (RMS) envelope of both muscles' signals using a moving window over 100 samples. To derive meaningful insights about the individual valence dimension of a participant's emotional state, I computed the change factor from baseline. More specifically, I divided the mean signal (e.g., corrugator activity) measured during a navigation phase by the mean signal of the participant's baseline measurement. Valence values were then computed by subtracting the change value of corrugator activity from the change value of zygomaticus activity.

4.2.6.5 Questionnaires and spatial orientation test

For the Short Stress State Questionnaire, I define the comparisons of the experimental treatments (time pressure and no time pressure) as the main goal of the measure and the comparisons of the pre and post measurements as secondary analysis. Therefore, I performed separate Bonferroni adjustments for each of these family of tests (Bender & Lange, 2001). For the SSSQ main analysis, six independent groups t-tests (two-tailed) were conducted with a Bonferroni adjusted alpha level of .0083 per test (α altered = .05/6), and for the SSSQ secondary analysis, six paired t-tests (two-tailed) were conducted with a Bonferroni adjusted alpha level of .0083 per test (α altered = .05/6). For the Simulator Sickness Questionnaire, I conducted four paired-sample t-tests (two-tailed) with a Bonferroni adjusted alpha level of .0125 per test (α altered = .05/4). In the spatial orientation test, the item score was the absolute deviation in angular degrees between the participant's response and the correct direction to the target. A participant's total score was the mean error across all items.

4.3 RESULTS

4.3.1 Navigation and map use

Overall, 47 of 48 participants completed the video gaming experience questionnaire. Eighteen participants reported playing video games on a regular basis. Of these, three participants reported playing once every half a year, seven participants reported playing monthly, and eight participants reported playing weekly. From leaving the virtual train until arriving at the destination, participants required 271.9 seconds on average. There was no significant difference in navigation time between the time pressure (M = 263.93, *SD* = 38) and no time pressure groups (M = 280.07, *SD* = 57.8), $t(79.3) = 1.60$, $p = .113$. On average, participants used the navigation aid for approximately 19.3 seconds during a complete navigation trial.

There was a significant difference in the ratio of navigation aid use over trial duration (the amount of time required to reach the destination) between the time pressure (M = 5.39%, *SD* = 2%) and no time pressure groups (M = 8.15%, *SD* = 5.5%), $t(57.664)= 3.24$, $p = .002$.

4.3.2 Manipulation check

4.3.2.1 Short stress state questionnaire

For the distress factor, there was not a significant difference between the groups, neither before the study, $t(46) = 0.38$, $p > .999$, nor after the study, $t(46) = 0.2$, $p > .999$. There was also not a significant difference of task engagement between time pressure and no time pressure groups, neither before the study, $t(46) = 0.08$, $p > .999$, nor after the study, $t(46) = -0.17$, $p > .999$. Before the study, there was a significant effect for the worry subscale between the time pressure (M = 9.67, *SD* = 5.29) and no time pressure groups (M = 5.50, *SD* = 3.94), $t(46) = -3.10$, $p = .02$, $d = 0.89$. After the study, worry was similar in the time pressure (M = 5.08, *SD* = 4.72) and no time pressure groups (M = 2.58, *SD* = 3.09), $t(46) = -2.17$, $p = .21$.

Paired comparisons between pre- and post-task SSSQ scores revealed that there was no significant increase in self-reported distress from pre- to post-task assessment in the time pressure group, $t(23) = -2.74$, $p = .070$, and in the no time pressure group, $t(23) = -2.64$, $p = .087$. In addition, there was not a significant change in task engagement before and after the study in neither the time pressure group, $t(23)= -0.76$, $p > .999$, nor the no time pressure group, $t(23)= -0.18$, $p = 0.857$. In contrast, performing the navigation task significantly decreased worry. Participants in the time pressure group had a mean decrease in worry scores of 4.58 (SD = 4.19), $t(23) = 5.36$, $p < .001$, $d = 1.0$. Participants in the no time pressure group had a mean decrease in worry scores of 2.91 (SD = 2.76), $t(23) = 5.17$, $p < .001$, $d = 1.1$. Figure 15 depicts how participants in time pressure and no time pressure groups scored on the three SSSQ subscales before and after the experiment.

4.3.2.2 Physiological recordings

The data of five participants were excluded from EDA analysis, and the data of one participant was excluded from fEMG analysis because a manual inspection of the data revealed many movement artefacts. As such, the EDA analyses were based on 43 participants.

Against our expectations, there was no significant effect of time pressure on the tonic level of skin conductance (after accounting for baseline) with similar scores for the time pressure ($M = 1.99$, $SD = 1.89$) and no time pressure groups ($M = 1.8$; $SD = 1.00$), $t(41) = 0.42$, $p = .676$. However, there was a significant difference in number of nonspecific skin conductance responses per minute (NS-SCRs/min) between time pressure conditions. More specifically, there was a higher frequency of NS-SCRs/min (after accounting for baseline) for the time pressure group ($M = 1.14$, $SD = 9.39$) than for the no time pressure group ($M = -5.99$, $SD = 12.21$), $t(41) = 2.15$, $p = .037$, $d = 0.66$.

There was no significant effect of time pressure on fEMG signal, with similarly negative valence scores (after accounting for baseline) in time pressure ($M = -0.11$, $SD = 0.77$) and no time pressure groups ($M = -0.05$, $SD = 0.72$), $t(44.964) = -0.25$, $p = .8$.

4.3.2.3 Simulator sickness

SSQ total scores revealed significant differences between pre-study ($M = 13.01$, $SD = 13.78$) and post-study ($M = 28.52$, $SD = 24.01$), $t(47) = -4{,}53$, $p < .001$, $d = 0.64$. This effect is composed of a significant increase in reported nausea symptoms, $t(47) = -4.36$, $p < .001$, $d = 0.61$, a significant increase in reported disorientation symptoms $t(47) = 5.48$, $p < .001$, $d = 0.59$, and a significant increase in reported oculomotor symptoms, $t(47) = -3.59$, $p = .003$, $d = 0.51$.

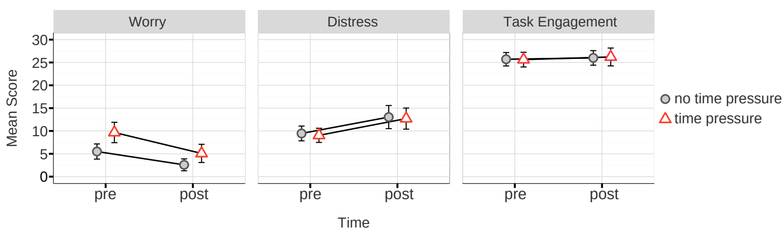

Figure 15: Mean scores of the worry, distress, and task engagement subscales of the Short Stress State Questionnaire (Helton, 2004) in the experimental conditions. Dots represent means and error bars represent 95% confidence intervals. Among the three subscales, only pre-task worry ratings significantly differed between the time pressure and no time pressure groups.

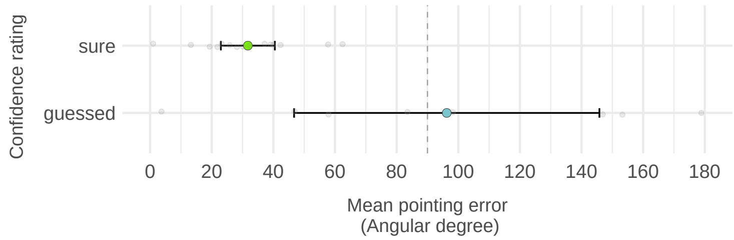

Figure 16: JRD errors on guessing trials suggest that chance performance was not biased (see Huffman & Ekstrom, 2018) but at 90 degrees. Dots represent means and error bars depict 95% confidence intervals.

In general, the manipulation checks indicate that participants in the time pressure group may have been more physiologically aroused (in terms of NS-SCRs/min) but not necessarily more distressed (in terms of the SSSQ and fEMG measures) than participants in the no time pressure group.

4.3.3 JRD results

Overall, the 48 participants produced 2112 JRDs. Mean angular error was 51.3° (SD = 47.6). The middle 50% of the data (IQR) ranges from 13.8° to 67.5° angular error. I calculated the mean error for each participants' "guessed" trials and tested whether the mean errors on the participant level differed from 90 degrees using a one-sample t test. Mean error on guessing trials was similar to 90 degrees ($M = 96.26$, $t(7) = 0.29$, $p = .774$). Furthermore, participants directional judgments that were rated with "I am very confident" ($M = 31.72$) were significantly more accurate than those judgments that were rated with "I have guessed" ($M = 96.26$, $t(7.54) = 3.02$, $p = .018$). Figure 16 depicts participants' mean JRD error of the "I have guessed" trials and the "I am very confident" trials. JRD errors of "very confident" trials were significantly lower than JRD errors of "guessed" trials and suggest that participants were able to assess their memory performance well, at least in cases of very high confidence.

4.3.3.1 Omnibus test

Absolute angular errors were submitted to an ART ANOVA with time pressure (with / without) and landmark type (local without global (a) / global without local (b) / local with global (c)) as factors. This omnibus test revealed a significant main effect for landmark condition $F(2,1676) = 8.91$, $p < 0.001$ indicating that there are at least two levels which show significantly different accuracy. However, there was no significant main effect of time pressure condition, $F(1,46) = 3.13$, $p = .083$, or interaction, $F(1,1676) = 0.663$, $p = .515$. Figure 17 shows the group differences between all experimental conditions in Study I.

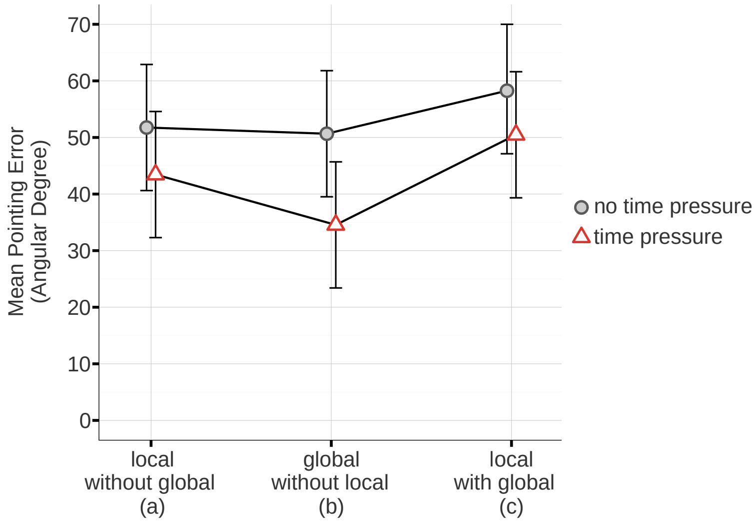

Figure 17: An omnibus ART ANOVA indicates that at least two of the levels within the landmark factor show different accuracy of directional judgments. Dots represent means and error bars depict 95% confidence intervals.

4.3.3.2 Time pressure and pointing to local and global landmarks

Absolute angular errors were submitted to an ART ANOVA with time pressure (with / without) and landmark type (local without global (a) / global without local (b)) as factors. This analysis revealed no significant main effect for time pressure, $F(1,46) = 3.77$, $p = .058$. Also, there was no significant main effect of landmark condition, $F(1,1102) = 0.49$, $p = .486$, or interaction, $F(1,1102) = 0.02$, $p = .325$. Inconsistent with our expectations, directional judgments for local landmarks were similarly accurate as directional judgments for global landmarks (Figure 17, contrast between condition a and b). The cell sizes, means, and standard deviations for the raw data of the 2x2 factorial design are presented in Table 2.

4.3.3.3 Time pressure and attentional narrowing

A mixed factorial ANOVA with time pressure (with / without) as a between-subjects factor and landmark condition (local without global (a) / local with global (c)) as a within-subject factor was computed for the mean absolute angular error of JRDs towards local landmarks. I did not observe a significant main effect for time pressure on absolute angular errors, $F(1,46) = 1.25$, $p = .27$. I also

Table 2: The table depicts cell sizes, means, and standard deviations for the raw observations (angular error) of the local without global (a) and global without local (b) conditions.

	Local (without global)			global (without local)			MM		
	n	M	*SD*	n	M	*SD*	n	M	*SD*
No TP	12	51.76	49.20	12	50.66	46.78	24	51.2	47.96
TP	12	43.44	44.70	12	34.55	34.84	24	39.00	40.28
MM	24	47.60	47.14	24	43.6	41.99			

TP = Time pressure, MM = Marginal means, n = number of observations, M = *mean, SD= standard deviation.*

did not observe a significant main effect for landmark condition, $F(1,46) = 2.77$, $p = .1$, or an interaction, $F(1,46) = 0.004$, $p = .95$. Inconsistent with our expectations, directional judgments for local landmarks were not improved by the presence of global landmarks (Figure 17, contrast between condition a and c). The cell sizes, means, and standard deviations for the raw data of the 2x2 factorial design are presented in Table 3.

Table 3: The table depicts cell sizes, means, and standard deviations for the raw observations (angular error) of the local (without global) and local (with global) conditions.

	Local (without global)			Local (with global)			MM		
	n	M	*SD*	n	M	*SD*	n	M	*SD*
No TP	12	51.76	49.20	12	58.26	49.75	24	55.01	49.54
TP	12	43.44	44.70	12	50.48	48.83	24	46.96	46.90
MM	24	47.60	47.14	24	54.37	60.50			

TP = Time pressure, MM = Marginal means, n = number of observations, M = *mean, SD= standard deviation.*

In the local with global (c) condition, I also assessed the mean absolute angular error for JRDs towards global landmarks (that were not highlighted). There was no significant difference between the time pressure group ($M = 62.15$, $SD = 51.30$) and the no time pressure group ($M = 68.15$, $SD = 48.48$), $t(46) = 0.93$, $p = .360$. However, a one-sample t-test showed that mean JRD error that was generated in the local (with global) condition was significantly different from a mean absolute angular error of 90° (chance), $t(47) = -7.67$, $p < .001$, indicating that participants acquired some knowledge about these landmarks. Mean performance aggregated over all groups was significantly better than chance ($M = 45.1$, $t(47) = -34.101$, $p < .001$)

4.3.4 Spatial Abilities and Strategies

Overall, perspective taking ability was not significantly correlated with mean absolute angular error, $r(94) = .2$, $p = .051$. Furthermore, perspective taking ability was not correlated with mean absolute angular error for neither the local without global condition, $r(46) = .14$, $p = .35$, nor the global without local condition, $r(46) = .27$, $p = .07$. There were also no significant correlations between orientation strategies (FRS) and JRD error.

4.4 DISCUSSION

Study I examined the effects of time pressure on survey knowledge acquisition for local and global landmark configurations during egocentric navigation in VR. After navigation, participants' survey knowledge accuracy was assessed with judgments of relative direction (JRDs). In the analysis, I examined the influence of time pressure on the accuracy of JRDs for local landmarks (e.g., a building along the route) and global landmarks (e.g., a tower in the distance). Specifically, I hypothesized that stress-related impairments of working memory have adverse effects on JRDs for local landmark configurations but have less adverse effects on JRDs for global landmark configurations. Addidionally, Study II investigated whether the mere presence of global landmarks supports survey knowledge acquisition for local landmarks. I hypothesized that the presence of global landmarks would facilitate survey knowledge acquisition for local landmarks, but only in the no time pressure group (i.e, attentional narrowing; Gardony et al., 2011). In the following, I will discuss the findings, limitations, and implications of the present study individually for these two main research questions.

4.4.1 Comparison of local and global landmark learning

Against our expectations of hypothesis 1, I found no advantage of global landmark configurations for survey knowledge acquisition with or without time pressure. Similarly, Castelli et al. (2008) demonstrated that survey knowledge for global landmarks was not better than survey knowledge for local landmarks after navigation through a virtual labyrinth. However, in the study of Castelli et al. (2008), both local and global target landmarks were available concurrently, so participants could use global landmarks as directional cues in order to mentally integrate other landmarks.

In contrast, there are several studies that could show that global landmarks improve survey knowledge acquisition during navigation (H. Li et al., 2016; Schwering et al., 2017; R. Li et al., 2014), but the learning tasks in these studies differed in central aspects from the present study. For example, H. Li et al. (2016) examined the benefits of actively attending a single global landmark during navigation on the development of local types of spatial knowledge, but the present study assessed the accuracy of mentally integrating multiple global landmarks into one coherent representation. Furthermore, R. Li et al. (2014) and Schwering et al. (2017) examined survey learning after global landmarks had been displayed from a top-down perspective on navigation devices. In contrast, the navigation aid in the present study did not depict landmarks, and survey knowledge was necessarily acquired from egocentric experience. To our knowledge, the present study was the first navigation study to compare the accuracy of survey knowledge towards multiple global landmarks to survey knowledge of multiple local landmarks.

Learning global landmarks in the present study was also different from R. Li et al. (2014) and Schwering et al. (2017) because it required participants to mentally integrate spatial locations over time spans of several minutes and after a considerable amount of movement. This process of path integration (e.g.,Klatzky et al., 1998) can improve the development of spatial knowledge (Riecke et al., 2007). A potential limitation of the study is that path integration may not have been helpful in the global landmark condition, because these landmarks were always placed in the distance instead of along the route. In contrast, relying on path integration strategies might have been beneficial in order to integrate the locations of local landmarks that were located along the route. If so, the effect of path integration may have counteracted the hypothesized advantage of global landmarks. Although this explanation is somewhat speculative, previous research has suggested that visual cues alone (e.g., optic flow, landmark piloting) may be sufficient for updating spatial positions and orientations (Kearns et al., 2002; Riecke et al., 2007; Mark May & Klatzky, 2000). In Study II of this dissertation, I aim to investigate the advantage of global landmarks located along the route. In comparison to Study I, the results of Study II aim to disentangle a spatial learning advantage of highly visible landmarks via path integration and a spatial learning advantage of highly visible landmarks via visual encoding from the distance.

4.4.2 Time pressure manipulation

In hypothesis 2a, I expected an increasing learning advantage of global landmarks under time pressure conditions because working memory resources should be impaired under stress. Contrary to our expectations, I did not find positive effects of global landmark configurations for mental integration, despite the heightened physiological arousal of participants under time pressure. The absence of a stress-related effect on spatial learning performance disagrees with other findings that indicate the improvement (Duncko et al., 2007) or impairment (Richardson & Tomasulo, 2011; Evans et al., 1984) of spatial knowledge acquisition under stress. In the present study, there was a trend that may have indicated an improvement for only global landmarks under time pressure. This lack of a significant effect could be due to low statistical power. For example, the present data was characterized by a high variance (SD = 47.6) and indications of participants suffering from simulator sickness symptoms. Simulator sickness might have introduced additional noise in the data. The ratings of participants indicated that they had symptoms of nausea, disorientation, and oculomotor problems. Future VR studies in CAVEs need to find efficient means to habituate participants to the simulator environment (Howarth & Hodder, 2008).

Other possible explanations for this null effect include the overall difficulty of the task used to assess survey knowledge (e.g., JRDs), the severity to which time pressure manipulation caused arousal, and the possibility of time pressure tapping into emotions other than distress. Time pressure may not have affected spatial memory if this particular manipulation only tapped the norepinephrine system and not the glucocorticoid system. Even though prior research has indicated that working memory functioning is affected by the norepinephrine system (e.g., Arnsten & Li, 2005), other research found evidence that impairment of working memory only occurs if the glucocorticoid system is simultaneously triggered (Elzinga & Roelofs, 2005). In the present data, this lack of neurobiological response patterns may be reflected by the low self-reported levels of distress for both time pressure and no time pressure groups. Indeed, among the self-report measures, I only found an effect of group assignment on pre-task worry ratings. This pattern could be attributable to the instructions regarding participants' compensation given before the experiment. In general, low self-reported distress may also indicate low workload (Matthews et al., 2002). Future studies can use a stronger manipulation of workload (e.g., spatial tapping; see Garden, Cornoldi, & Logie, 2002) and/or measure both physiological arousal and cortisol level directly. With respect to the difficulty of the task used to assess survey knowledge, additional training on the JRD task (before the main experiment and with different stimuli) may reduce the overall variability among individuals and increase statistical power.

4.4.3 Attentional Narrowing

In Study I, the mere presence of global landmarks did not appear to improve survey knowledge acquisition for local landmark configurations (compared to when global landmarks were absent) for either the time pressure or the no time pressure group. This does not confirm hypothesis 2b. This result indicates that visible global landmarks are either not used spontaneously during navigation or do not improve spatial memory for local landmark configurations. Previous research using different versions of the Morris water maze task (Gardony et al., 2011) have found that global landmarks help participants find hidden goal locations compared to searches with only local landmarks, but in the present study, the information provided by global landmarks may have been redundant with the information provided by other sources (e.g., navigation aid and/or optic flow via path integration). In addition, the participants may have allocated more attention to the navigation task than to the spatial memory task, as evidenced by the high JRD errors overall. In order to address this possibility, future research could focus on attention allocation during navigation through a large-scale virtual environment using eye tracking.

4.4.4 Perspective taking abilities

The present data implies no strong support for a relation of perspective taking ability and participants' ability to acquire survey knowledge from VR. This does not confirm hypothesis 3 and is in conflict with prior evidence that has shown that with increasing perspective taking ability people show improved ability to acquire survey knowledge from direct navigation (Fields & Shelton, 2006). However, the correlation in the present study narrowly missed the significance level (i.e. $p = 0.51$). Again, this could be due to low statistical power that was introduced by simulator sickness symptoms. Conversely, low power should not affect local and global landmark learning differently. Hence, the present data implies that the encoding of simultaneously visible global landmarks similarly engages perspective taking processes than the encoding of sequentially visible local landmarks.

Chapter 5

STUDY II

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Study I did not show a significant improvement in survey knowledge acquisition for global landmark configurations as compared to local landmark configurations in situations with or without time pressure. One possible explanation for this result is that the global landmarks were placed at a great viewing distance while local landmarks were placed along the route. Participants could not take advantage of path integration to acquire global landmark knowledge (Section 2.1.1), and the advantage of path integration for learning local landmark configurations may have offset any advantages of simultaneous visibility for learning global landmark configurations (Meilinger, Strickrodt, & Bülthoff, 2016; Ruotolo et al., 2012). Thus, in Study II, I aimed to further assess the accuracy of survey knowledge acquisition for local and global landmarks when they are both located along the route. Figure 18 illustrates the placement of landmarks along the route and the visibility of local as compared to global landmarks.

Given that participants in Study I did not show a significant increase in distress ratings due to the time pressure manipulation, I reasoned that participants' working memory (WM) was not significantly impaired (Matthews et al., 2002). In Study II, I therefore aimed to impair working memory functioning more directly using a concurrent spatial task. Concurrent tasks interfere with the active processing of information in WM and are used in this study to reveal the learning utility of both local and global landmarks when learners operate on limited cognitive resources. For example, participants may have limited cognitive resources while experiencing stress or conducting multiple concurrent tasks during navigation (Wen et al., 2011, 2013; Gras et al., 2013; Meilinger et al., 2008). Prior research has also demonstrated that concurrent task demands result in increased cognitive load, increased psychophysiological arousal (Engström, Johansson, & Östlund, 2005), and increased self-reported distress (Matthews et al., 1999). The observed effects of the present study cannot be used to draw conclusions about the isolated role of psychophysiological stress for spatial learning because, in addition to the stress effects, participants are also distracted from spatial learning by the concurrent task. However, learning and navigating under concurrent task load is expected to be a realistic simulation of assisted navigation and

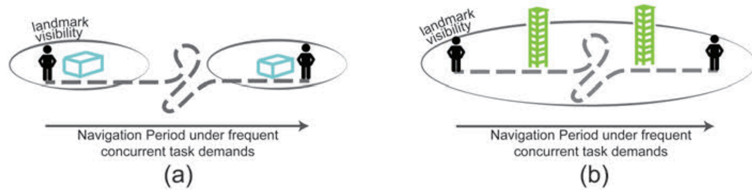


Figure 18: The present study tests whether working memory resources are required to different extents when learning local and global landmark configurations along the route. (a) In order to integrate local landmarks into a survey representation, I expect that long temporal intervals without simultaneously visible landmarks draw strongly on working memory resources. The spatiotemporal intervals between exposures to individual landmarks should require users to update the spatial relationship between their own body and relevant surroundings. (b) In order to represent simultaneously visible global landmarks in a survey representation, learning is not complicated by long spatiotemporal intervals.

will be used to draw conclusions about survey knowledge acquisition during such situations.

5.1 RESEARCH QUESTIONS

In Study II, I will investigate the following research questions defined in Chapter 1. Notably, Study II investigates the effects of stress on survey knowledge acquisition from local and global landmarks using a concurrent spatial task.

1. How accurate is the construction of survey knowledge from local and global landmarks when both are located along the route?
2. How does stress during navigation (operationalized as concurrent task load) interfere with successful survey knowledge acquisition?
   a) What is the impact of higher concurrent task demands on the integration of sequentially visible local landmarks compared to simultaneously visible global landmarks into a common survey representation?
3. What is the role of working memory in survey knowledge acquisition for local and global landmarks under stress?

In addition to these core questions, I will examine whether the experimental manipulations affected participants' confidence in their responses (Section 3.3.2.2) and whether participants were able to successfully judge the accuracy of their spatial memory across all experimental conditions. In order to investigate these questions, Study II asked participants to navigate through virtual cities. I manipulated participants' attention towards local or global landmarks and whether or not the experimental task included a concurrent task. I also assessed individuals' WM capacities because I expected high WM capacities to benefit the integration of local landmarks over time (Münzer et al., 2006) and hence support survey knowledge acquisition.

5.2 METHODS

5.2.1 Participants

The study was conducted in German. Participants were recruited via the psychology recruitment server from the University of Zurich (psychologie.uzh.ch/probandenserver/). Fifty-four people participated in the study for monetary compensation. The sample size of fifty-four participants with twenty-seven in each between-subjects condition was determined before data collection. Two participants did not complete the study due to slight nausea. Fifty-two participants between the ages of 18 and 36 (M = 25.6 years, *SD*=4.5, 26 women) completed all of the experimental tasks.

5.2.2 Ethics statement

All of the procedures performed in this study were performed in accordance with the ethical standards of the Swiss Psychological Society and the American Psychological Association.

5.2.3 Materials

5.2.3.1 Apparatus

I employed the same setup as in Study I (Section 3.2). Figure 19 shows a photograph of a participant in the CAVE during the experiment. As compared to Study I, this time, a 70 cm tall cabinet was placed next to the participant (on the side of the dominant hand) and functioned as an armrest and table for the numeric keypad. Also different from Study I was that participants navigated through virtual cities using a foot-operated control interface (3D Rudder, Aix-en-Provence, FR; www.3drudder.com). Forward or backward movement required participants to tilt the interface with their feet towards the front or back, respectively. Tilting the 3D rudder interface to the right or left resulted in rotating the view to the right or left, respectively. To ensure the usability of these controls and avoid simulator sickness, I tested virtual navigation with three participants in a pretest. I found that slow rotational acceleration was perceived as unpleasant. Consequently, I increased this value to a point where participants reported feeling comfortable (maximum rotation speed was reached in 0.1 second). However, acceleration was perceived differently for movement (trans-

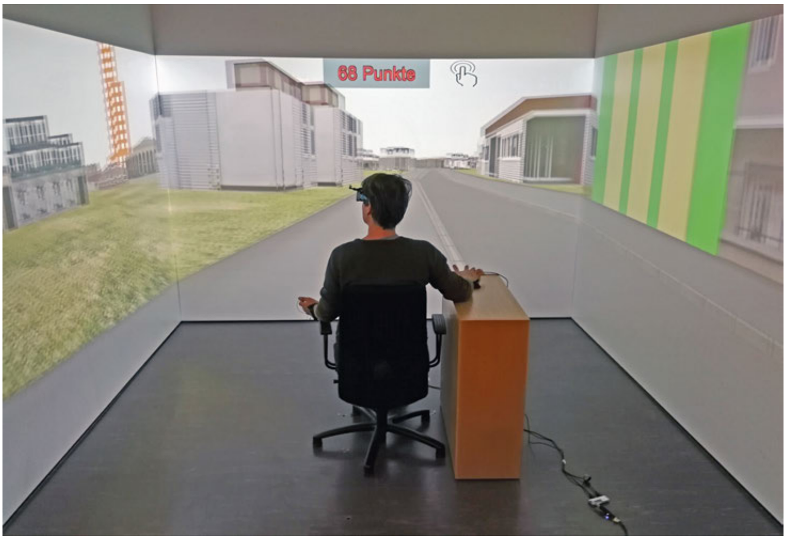


Figure 19: Photograph of the experimental setup with the participant sitting on a chair 30 cm back from the center of the VR system (CAVE).

lation), where participants described a slower level of acceleration as natural. For movement acceleration, I adopted the value from study I (maximum speed was reached in 1.5 second). The experimental tasks were rendered with Vizard 5.6 (WorldViz, CA, USA; www.worldviz.com). The city models were designed using City Engine 2014 (Esri, CA, USA; www.esri.com/). Electrodermal activity (EDA) was recorded using AcqKnowledge 4.4 (Biopac Systems, CA, USA) and analyzed using LedaLab, a Matlab-based software for analyzing skin conductance data (Benedek & Kaernbach, 2010). EDA recordings from AcqKnowledge were synchronized in real-time with the experimental procedure from Vizard.

5.2.3.2 Virtual Environments

The two city models used for navigation each had an area of approximately 0.4 km^2 that was covered with buildings, trees, streets, and open spaces. Except for four high-rise buildings (80 m to 100 m tall), the cities contained low-rise buildings with heights between 5 m and 15 m. The sidewalk widths of all streets were 5 m, and the widths of the streets that were part of the navigated routes were all 7 m. Approximately one-fifth of each city block was covered with open space instead of buildings. The cities were flat without any slopes, hills, or mountains. Figure 20 depicts a top-down view of the street network and the routes in each city.

For each city, I selected a set of four low-rise buildings and four high-rise buildings located along the route. Depending on the landmark condition, either the set of low-rise buildings or the

Figure 20: Each route was approximately 950 m long. Double squares (green) represent the landmark locations in the global condition, and single squares (blue) represent the landmark locations in the local condition.

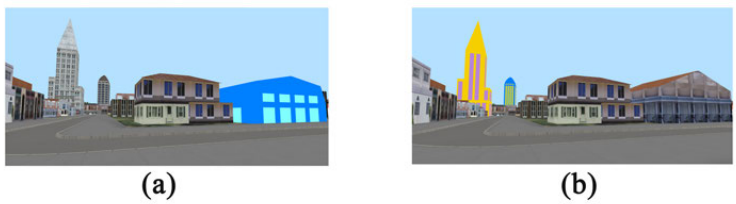


Figure 21: Screenshots of one of the virtual cities in each of the two landmark conditions taken from the same viewpoint. (a) In the local landmark condition, a set of four local landmarks are highlighted. (b) In the global landmark condition, a set of four global landmarks are highlighted. The same buildings were present in both conditions, but only the target buildings were highlighted.

set of high-rise buildings was highlighted. Due to the surrounding buildings, low-rise buildings were strongly restricted in visibility (i.e., local landmarks), and participants could only perceive one at a time (i.e., sequential viewing). In contrast, high-rise buildings were relatively tall and visible from multiple proximate and distant locations along the route (i.e., global landmarks), and participants could view more than one at a time (i.e., simultaneous viewing). Figure 21 depicts one of the virtual cities from the participants' viewpoint but in different landmark conditions.

During the navigation task, participants could display a visual routing assistant in the center of the front screen of the CAVE, including a map of the city with a footprint of 0.026 km² and a 1:156 map scale. The map depicted the location of the user at its center and was oriented with respect to the user's heading direction. The map contained the street network and the highlighted

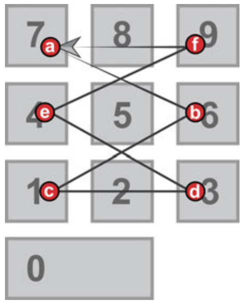


Figure 22: Concurrent to navigation, one group of participants had to continuously tap a spatial pattern on a numeric pad. The illustration shows the correct order of the six-number sequence with a-b-c-d-e-f.

route towards the destination but did not depict buildings or landmarks. While the map was displayed, the side screens turned black and movement through the virtual environment was disabled until three seconds after using the map. The design of this navigational aid was inspired by contemporary designs and aimed to facilitate route-following while hindering survey learning directly from the map itself.

5.2.3.3 JRDs

To assess participants' memory for relative spatial relations, I employed a CAVE version of the JRD task (Section 3.3.2.1). Participants were asked to imagine standing at a first landmark while facing a second landmark and to point to a third landmark. I used the same sampling procedure as in Study I which selected one of each symmetrical trials (e.g., ABC or ACB). Overall, this resulted in participants performing 12 JRD trials per landmark condition.

5.2.3.4 Spatial tapping task

A spatial tapping task introduced additional processing demands concurrent to navigation and learning the landmark configurations. The spatial tapping task involved the continuous typing of a predefined series of six numbers (7–6–1–3–4–9) at a rate of one keystroke per second on a 3x3 matrix numeric pad (Figure 22). To improve blind tapping, I removed keys that were not part of the tapping task. The tapping sequence was inspired by the pattern used by Labate et al., 2014.

5.2.3.5 Test and questionnaires

To assess participants' WM capacities, the Symmetry Span Test (Kane et al., 2004) presented locations one at a time as filled grid cells in a 5x5 matrix. Each participant's primary task was to recall a sequence of locations after the presentation phase was finished. Between the presentations of different locations, a processing task required participants to judge the symmetry of a pattern displayed in an 8x8 matrix. For each of 13 trials, the memory sequences ranged from 2 to 6 cells. I also administered two questionnaires. In the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993), participants rated 16 symptoms on a 4-point scale from absent to severe. These ratings were used to generate scores for three subscales (i.e., nausea, disorientation, and oculomotor symptoms) and a total score. In the Short Stress State Questionnaire (SSSQ), participants responded to questions that indicated their feelings of distress, engagement, and worry (Helton, 2004). Both questionnaires were administered once before (pre-task) and once after (post-task) the experiment.

5.2.3.6 Gamification

A scoring system was used to motivate participants. Participants' overall scores were visible at the top of the front screen throughout the experiment, and participants knew that their compensation (between 10 CHF and 20 CHF) would depend on their score. Specifically, I told participants that their overall scores changed with their performance on the navigation, tapping, and JRD tasks. Participants lost one point every 10 seconds during the navigation phase and could earn points via accurate performance on JRD trials. After finishing one set of JRD tasks, a pointing accuracy score was displayed and added to the overall score. This score was computed by subtracting the mean angular error of 12 JRD trials from 180. In order to avoid strategic trade-offs, participants were instructed that a "good" overall score could only be achieved when all tasks were performed well. However, participants were not told the exact manner in which their overall scores were computed. Only during tapping was a 1-point penalty subtracted from a participant's score during navigation if their mean tapping rate was slower than one hit per second for longer than three seconds. Furthermore, hitting an incorrect key resulted in a penalty of 0.5 seconds added to the mean tapping rate. A beeping sound and a symbol appearing on the top of the front screen signaled every time the system subtracted a point due to insufficient or incorrect tapping activity.

5.2.4 Procedure

Participants were tested individually. After participants received a standardized overview of the experimental tasks, they provided informed consent. Then the participants completed the pre-task tests and questionnaires (i.e., SSQ, SSSQ, Symmetry Span Test) on a desktop computer. Subsequently, the experimenter cleaned the

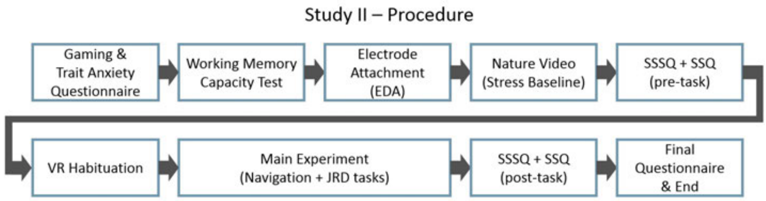


Figure 23: The procedure of Study II visualized as a flow chart. EDA = Electro dermal activity, SSSQ = Short stress state questionnaire, SSQ = Simulator sickness questionnaire

skin at the medial phalanges of participants' index and middle fingers with a light abrasive gel and attached solid gel electrodes at these locations (Figner & Murphy, 2011). After electrode functionality was verified, participants rested for two minutes to ensure the hydration of the skin by the gel. Next, participants watched a 150-second nature video projected on the front screen of the CAVE. EDA recordings during this video were used as a baseline to account for individual differences in physiological reactivity to acute stress states or external workload (Ulrich, 1981). Next, the participants read the instructions for the upcoming tasks. In the CAVE, participants first practiced with the controls by collecting items in a virtual environment using the 3D rudder. After completing this task successfully, the participants were led through all components of each experimental trial (e.g., navigation, map use, and the JRD task) by the experimenter. I designed an extra city for this training trial. Once the participants in the group without tapping had no further questions, the experimenter started the main experiment. Participants in the tapping group received the same introduction except that the experimenter introduced the tapping procedure during a predefined interval in the training task. Participants finished the last 50 m of the navigation task while performing the tapping task concurrently. Then I recorded baseline measurements of performance on the tapping task. Participants were instructed to tap as accurately and quickly as possible for 30 seconds. After this baseline measurement, and if a participant had no further questions, the experimenter started the main experiment.

The main experiment consisted of two blocks. Each experimental block consisted of a train ride, a navigation task, and a series of JRDs. The train ride brought participants to the start point of the route. After the train ride, the participant's viewpoint was moved out of the train automatically to begin the navigation task through the city. During the navigation phase, participants were asked to follow the route indicated on the navigational aid as quickly as possible and to memorize the relative locations of the highlighted landmarks as accurately as possible. The number of highlighted landmarks was initially unknown to the participants. Participants were instructed explicitly not to prioritize one of the given tasks (i.e., following the route, memorizing the landmarks, or tapping). Participants were also asked not to stray from the route marked on the navigational aid. When a participant left the route, a message appeared asking them to return to the marked route. Participants finished the navigation task when they arrived at the destination. After each navigation trial, participants' survey knowledge was assessed using 12 JRDs. Pointing accuracy was computed automatically by the system. After each JRD, participants indicated their pointing confidence on a continuous rating scale between "very unconfident" and "very confident". After the main experiment, participants completed the post-task SSQ and SSSQ questionnaires.

5.2.5 Hypotheses

1. The acquisition of globally visible landmarks is generally more accurate than the acquisition of locally visible landmarks.
2. Concurrent task demands disrupts the mental integration of landmarks in a survey representation via working memory.
   a) Disruption of survey knowledge acquisition is stronger for sequentially visible local landmarks than for simultaneously visible global landmarks.
   b) Concurrent task demands also result in increased psychophysiological arousal (assessed as EDA) and increased self-reported distress (indicated by self-report).
3. High WM capacities improve the sequential integration of local landmarks more strongly than the simultaneous integration of global landmark configurations. Therefore, I expect a stronger positive relation between WM capacity and local landmarks than between WM capacity and global landmarks.

In addition to these core hypotheses, I expect that participants are able to judge their own memory quality. Hence, their confidence ratings should follow the same trend than JRD error.

5.2.6 Design & Analysis

This Study included two categorical independent variables in a 2 (with / without tapping task) x 2 (local / global landmarks) mixed factorial design. Participants were randomly assigned to either the with or without tapping group (i.e., between-subjects), but all participants completed both landmark conditions (within-subjects in a counterbalanced order). WM capacity was also included as an observed continuous explanatory variable. Dependent variables included JRD error, the SSQ and SSSQ data, tapping data, and EDA.

5.2.6.1 JRDs

JRD error was defined as the absolute angular difference between the estimated direction and the actual direction of a target relative to the reference landmarks. These angular errors could vary between 0° (very accurate) and 180° (very inaccurate). The errors were analyzed with linear mixed effects models using the lmer function from the "lme4" package (version 1.1-18-1; Bates, Mächler, Bolker, & Walker, 2015) implemented in R version 3.5.2 (R Core Team, 2018). Models were fitted using restricted maximum likelihood estimations. P-values were derived using the R package "lmerTest" (Kuznetsova, Brockhoff, & Christensen, 2017) which applies Satterthwaite approximations of degrees of freedom. Post-hoc marginal effect estimations were computed using the R package "emmeans" (version 1.3.2; Lenth, 2019).

5.2.6.2 WM capacity

One participant performed below 85% accuracy in symmetry judgments and was excluded from the WM capacity analysis. Low performance in symmetry judgments indicates that the participant prioritized the memory task. In such a case, WM capacity measures do not accurately represent working memory performance anymore (see Kane et al., 2004). To compute participants' WM capacity, I used a partial-credit unit scoring (PCU) method. Empirical results favor partial-credit unit scoring because credit is given to fully and partially correct answers (e.g., Conway et al., 2005).

5.2.6.3 Questionnaires

For the SSQ, I applied the established weighting score procedure developed by Kennedy and colleagues (1993) to obtain a single score for each of the three subscales and a global index that reflected the overall discomfort level. I conducted four paired-sample t-tests (two-tailed) with a Bonferroni adjusted alpha level of .0125 (.05/4) per test. For the SSSQ, I computed scores by averaging across the eight items of each subscale (Helton, 2004). From these averages, I computed change scores by subtracting the pre- from the post-task score.

5.2.6.4 Tapping data

To examine mean differences in change scores between the with and without tapping groups, I conducted independent-samples t-tests (two-tailed) for each of the three subscales (distress, engagement, worry) with a Bonferroni adjusted alpha level of .01666 (.05/3) per test. For the tapping data, I computed the number of correct tapping responses per second (correct tapping rate) for each navigation trial and the baseline trial. I performed paired-sample (two-tailed) t-tests with a Bonferroni adjusted alpha level of .025 (.05/2) per test to understand whether participants' tapping performance during navigation changed significantly from their baseline measurement and whether that change was similar between landmark conditions.

5.2.6.5 EDA

I extracted the EDA signal at 1000 Hz and down-sampled to 10 Hz without applying any post-hoc filters. I excluded three participants from the analysis due to substantial movement artifacts in the signal. Then I conducted a continuous decomposition analysis to decompose the raw signal into continuous tonic and phasic activity (Benedek & Kaernbach, 2010). Arousal was operationalized as a positive change in the tonic component of EDA (i.e., skin conductance level or SCL) or as an increase in non-specific skin conductance responses per minute (NS-SCRs/min, Boucsein, 2012). To check the expected difference in arousal between the with and without tapping groups, I submitted the mean EDA increases from baseline to independent-samples t-tests (two-tailed) with a Bonferroni adjusted alpha level of .025 (.05/2) per test.

5.2.6.6 Structure of statistical models

5.2.6.7 JRD model

To identify the maximal appropriate random effects structure that would converge, I devised a model that included JRD errors as a dependent variable, no fixed effects, and a maximal random effects structure that was qualified by the experimental design (Barr, Levy, Scheepers, & Tily, 2013). At this point, the random structure included by-subject and by-item intercepts and slopes. I defined the random effects at the item-level as the variance that was introduced by the sampling of landmark triples for each JRD trial. All JRD trials that involved the same three landmarks (e.g., local landmarks A, B, and C in city 1) were defined as an item. Next, I simplified this maximal random effects structure until the model converged by first successively excluding random slopes and then random intercepts. The first model that converged included by-subject intercepts and slopes and by-item intercepts. Note that the model accounts for correlations across data points that result from differences in participants' overall performance (e.g., generally better memory for different participants) and from changes in performance across landmark conditions.

The fixed effects model structure followed a confirmatory hypothesis-driven approach with two main effects (landmark type, spatial tapping), one covariate (WM capacity), and any interactions between these three factors. I also included the trial number as a fixed effect in order to account for the variance that is related to a general practice effect. The full regression model used effects coding with contrasts set to -0.5 and +0.5 for each categorical predictor and with the continuous variable centered (not scaled) at the mean value for the WM capacity (M = 0.655). The lmer formula of the full JRD model with all fixed and random factors is displayed in Equation (1).

$$\begin{aligned}&\mathrm{JRD\ error} \sim \mathrm{landmark\ type} * \mathrm{spatial\ tapping} *\\&\mathrm{WMcapacity} + \mathrm{trial\ number} + (1 \mid \mathrm{triple}) +\\&(1 + \mathrm{landmark\ type} \mid \mathrm{participant})\end{aligned} \tag{1}$$

Levene's test revealed that the residual variance was not homogeneous across experimental conditions (F = 3.98, p < .001). A log transformation resolved this violation of the homogeneity assumption according to a subsequent Levene's test (F = 0.92, p = .597). Because both models demonstrated the same pattern of results, I report only the non-transformed data below for readability. For the log transformed results, see Figure 38 in Section A.2). Regression plots were created using the R package "sjPlot" (version 2.6.2; Lüdecke, 2018).

5.2.6.8 Confidence model

Employing participants' confidence ratings as dependent variable in a regression model allows to understand the experimental factors that influenced participants pointing certainty. The fixed effects structure is displayed in Equation (2). It was the same fixed effects structure like in Equation (1), but the JRD errors were included as predictors. However, Levene's test revealed that the residual variance in confidence ratings was not homogeneous across experimental conditions (F = 5.26, p< .001). A log transformation could not resolve this violation of the homogeneity assumption according to a subsequent Levene's test (F = 12.48, p< .001). Therefore, I transformed the data into an ordinal variable with three equal intervals (0 - $0.\overline{3}$ = low, $0.\overline{3}$ - $0.\overline{6}$ = medium, $0.\overline{6}$ - 1 = high). The data was then fitted using a proportional odds logistic regression model with the polr function from the MASS package (Venables & Ripley, 2002). Such a model allowed me to compute the probabilities of low, medium, or high confidence ratings, and how these probabilities are affected by changes in any of the predictor variables.

$$\begin{aligned}&\mathrm{confidence\ ratings} \sim \mathrm{landmark\ type\ spatial\ tapping}\\&+\mathrm{JRD\ error} + \mathrm{WM\ span} + \mathrm{trial\ number}\end{aligned} \tag{2}$$

Before interpreting the coefficients, I tested the parallel slopes assumption by calculating a series of binary logistic regressions with varying interval borders on the ordinal dependent variable. The assumption holds that the effect of each predictor on the odds of an event (i.e. the logarithmic of the odds) are the same for every level of that category. Using the probability estimates of the binary models, I checked the equality of coefficients across interval borders using a graph (Harrell J, 2015). Generally, the results indicated that all predictors hold with the parallel slopes assumption with increased deviation in the tapping condition. Results of the tapping variable should be interpreted with caution (see Figure 39 in Section A.2).

5.3 RESULTS

5.3.1 Navigation and map use

On average, our 51 participants required 296 seconds to move from the starting point to the destination of each navigation trial. Participants in the tapping group (*M* = 311, *SD* = 33.7) required more time to reach the destination than participants in the group without tapping (*M* = 281.18, *SD* = 17.43), $t(49)= 3.96$, $p< .001$, $d = 1.11$. Participants used the navigation aid for 18 seconds (or 6%) of the time they spent on the navigation task. There was no significant difference in the absolute duration of navigational aid use between the tapping group (*M* = 19.62, *SD* = 10.28) and the group without tapping (*M* = 16.43, *SD* = 6.02; $t(49)= 1.36$, $p = .180$). Similarly, when the duration of navigational aid use was normalized with respect to trial duration, there was no significant difference between the tapping group (*M* = 6.20%, *SD* = 2.71%) and the group without tapping (*M* = 5.85%, *SD*=1.95%; $t(49) = 0.53$, $p = .597$).

A pearson's chi-square goodness of fit test was performed in order to determine if the number of wrong turns in the tapping and without tapping group differed from the expected equal distribution. There was a significant difference in the number of wrong turns between the tapping (35) and the without tapping (19) group $\chi2$ (1) = 4.7407, $p = 0.02946$. Figure 24 depicts the navigation errors and its spatial distribution along the routes of both environments.

Concerning participants' individual spatial abilities in each treatment group, there were no significant difference in WM capacity between the tapping group (*M* = 0.688, *SD* = 0.177) and the group without tapping (*M* = 0.642, *SD* = 0.148; $t(49) = 0.98$, $p = .332$).

5.3.2 Manipulation check

For the SSQ, I found that the total scores increased significantly from pre-task (*M* = 17.97, *SD* = 17.12) to post-task (*M* = 29.7, *SD*=30.9) measurements, $t(50) = -3.27$, $p = .007$, $d = -0.46$. This increase in total score was qualified by significant increases in nausea $t(50)= -2.94$, $p = .020$, $d = -0.41$, and disorientation, $t(50)= -4.27$, $p< .001$, $d = -0.6$. There was no increase in oculomotor symptoms, $t(50)= -1.35$, $p = .185$. Furthermore, the increase in total SSQ score

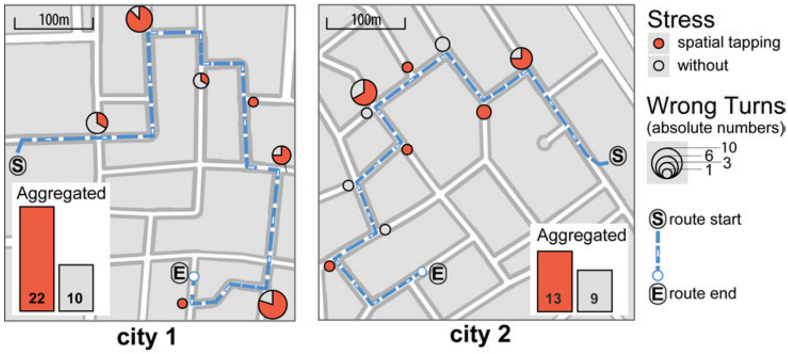


Figure 24: Participants in the tapping group took more wrong turns than participants in the without tapping group.

was similar for the tapping group (M = 8.53, *SD*=19.92) and the group without tapping (M =14.82, *SD*=30.19; t(49) = 0.87, p = .738).

The SSSQ data indicated a significant effect of the tapping task on participants' affective states. Participants in the tapping group showed a larger increase in distress ratings (M = 0.9, *SD*=0.77) than participants in the group without tapping (M = 0.31, *SD*=0.77; t(49)= 2.75, p = .025, d = 0.77), indicating an increase in cognitive load. In contrast, tapping did not affect engagement significantly, with similar increases from pre- to post-task measurements in the tapping group (M = +0.21, *SD*=0.54) and the group without tapping (M = +0.19, *SD*=0.51; t(49)= 0.86 , p> .999). Similarly, the tapping task had no significant effect on worry ratings t(49) = -0.94, p> .999, with the tapping group (M = -0.53, *SD*=0.62) showing similar decreases in worry ratings to the group without tapping (M = -0.68, *SD*=0.51). Figure 25 shows the mean ratings of both experimental groups for each subscale before and after the task.

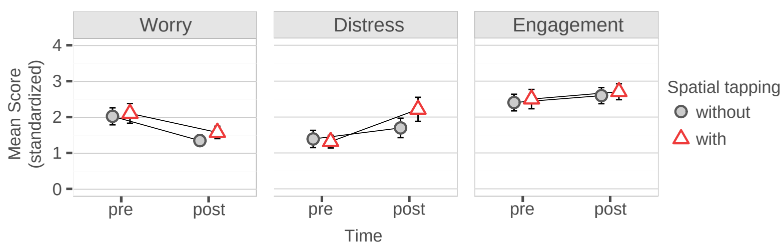


Figure 25: Mean self-reported distress, engagement, and worry for both groups (with / without tapping). Participants' self-reports were taken before and after the experimental procedure. Increases in distress were significantly higher for the tapping group than for the without tapping group.

For the 25 participants in the tapping group, the correct tapping rate decreased significantly between baseline measurements (M =

3.72, *SD*=1.21) and navigation trials (*M* = 2.06, *SD* = 0.65; t(24) = -8.41, p< .001, d = -1.68), suggesting that navigation and tapping required the same set of cognitive resources. However, the correct tapping rate decreased similarly from baseline for local (*M* = -1.71, *SD*=0.97) and global (*M* = -1.62, *SD*=1.06) landmark configurations, t(24)= 0.92, p = .730, suggesting that local and global landmark learning relied to similar extents on spatial WM resources (Rudkin, Pearson, & Logie, 2007).

For the EDA data, participants in the tapping group demonstrated a similar increase of SCL from baseline (*M* = 3.01, *SD* = 1.87) than participants in the without tapping group (*M* = 2.01, *SD* = 1.48; t(46) = 2.06, p = .09). Furthermore, there was no difference in NS-SCRs/min between the tapping group (*M* = -0.09, *SD* = 0.24) and the without tapping group (*M* = -0.12, *SD* = 0.22; t(46) = -0.37, p > .999).

5.3.3 JRD Results

Overall, the 51 participants produced 1224 JRDs. The mean angular error was 55.67° (SD = 47.77°), and the median angular error was 38.5°. The interquartile range ran from 17.79° to 85.62° in angular error. For a complete table of statistics from the JRD analyses, see Figure 27. Mean error on guessing trials was significantly shifted from 90 degrees with a mean JRD error of 76.89 degree (t(22) = -2.73 , p = .012). Participants directional judgments that were rated with "I am very confident" (*M* = 23.61) were significantly more accurate than those judgments that were rated with "I have guessed" (*M* = 76.89, t(29.7) = 7.922, p < .001). Figure 26 depicts participants' mean JRD error of the "I have guessed" trials and the "I am very confident" trials.

The linear mixed effects model revealed significant main effects for landmark type, tapping group, WM capacity, and trial number, as well as a significant interaction between landmark type and

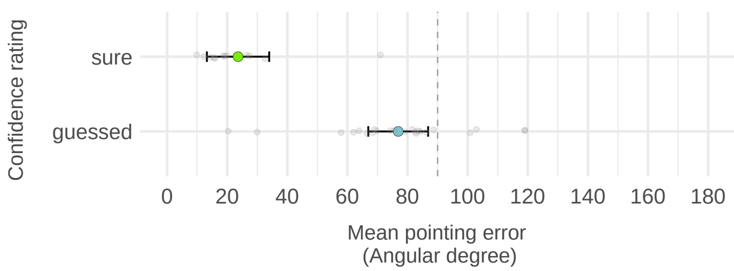
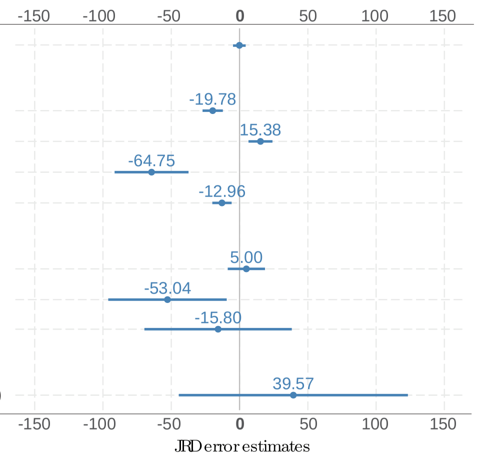


Figure 26: JRD errors on guessing trials suggest that chance performance was slightly shifted to 76.89 angular degree. Dots represent means and error bars depict 95% confidence intervals.

		Std. Error	df	t value	p	95% CIs
Intercept	56.01	2.35	35.45	23.80	< 0.0001	(51.39 , 60.62)
Main E ects						
LM (global) ***	-19.78	3.81	26.04	-5.18	< 0.0001	(-27.25 , -12.30)
TAP (with) **	15.38	4.50	47.35	3.42	0.0013	(6.56 , 24.20)
WM capacity (0.5) ***	-64.75	13.88	47.45	-4.66	< 0.0001	(-91.97 , -37.54)
trial_number (2) ***	-12.96	3.63	46.28	-3.57	0.0009	(-20.09 , -5.84)
Two-Way Interactions						
LM x TAP	5.00	7.005	46.16	0.71	0.4789	(-8.73 , 18.73)
LM x WM capacity *	-53.04	22.24	46.02	-2.38	0.0212	(-96.64 , -9.44)
TAP x WM capacity	-15.80	27.67	46.96	-0.57	0.5707	(-70.05 , 38.43)
Three-Way Interaction						
LM x TAP x WM capacity	39.57	43.00	45.37	0.92	0.3623	(-44.71 , 123.86)



LM = Landmark Type; TAP = Spatial Tapping; WM = Working Memory, CIs = Con dence Intervals

*** $p < .001$; ** $p < .01$; * $p < .05$

Figure 27: A list of the fixed effects regression coefficients using orthogonal contrasts. The intercept is the grand mean, and other coefficients are the estimated differences between a group mean and the grand mean. Confidence intervals were computed using the Wald test. There were significant main effects found for landmark type, tapping, WM capacity, and trial number. Interestingly, the two-way interaction indicated that the effects of landmark type and WM capacity varied with respect to each other.

WM capacity. Specifically, participants in the tapping group had a significantly higher JRD error than participants in the without tapping group. Still, a one-sample t-test revealed that JRD performance in the tapping group was better than chance level ($M= 61.97$, $t(24)= -3.91$,$p < .001$). The tapping group effect did not interact with landmark type or WM capacity. Participants' JRDs also improved, on average, by 12.96 degrees from the first trial to the second trial, suggesting a general practice effect. In addition, the significant main effects of WM capacity and landmark type are qualified by a two-way interaction. In order to understand the manner in which WM capacity moderated the effect of landmark type on JRD error, I modeled the marginal effects of WM capacity on JRD errors separately for local and global landmark configurations (averaged over levels of the other factors). Figure 28 visualizes the relationship between JRD error and WM capacity with separate regression lines for local and global landmarks.

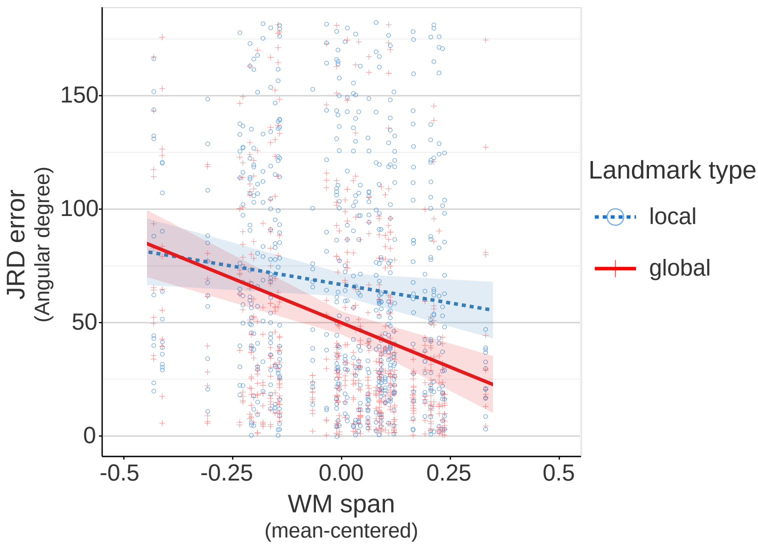


Figure 28: Predicted estimates of JRD error as a result of WM capacity and landmark condition. The model predicted that with increasing WM capacity, the error would decrease more for global landmark representations than for local landmark representations.

This plot suggests that participants with higher WM capacities benefit from global landmark configurations more than from local landmark configurations during navigation for spatial learning. After testing each of these two regression lines, I demonstrated that JRD errors for local landmark configurations did not significantly decrease with higher WM capacity, $\beta = -38.7$, $SE_{\beta} = 17$, $t(48) = -2.15$, $p = .073$, 95% CI [-74, -2.5]. However, WM capacity strongly affected JRD errors involving global landmark configurations, $\beta = -91.1$, $SE_{\beta} = 18$, $t(48) = -5.1$, $p < .001$, 95% CI [-127, -55.3]. Finally, contrary to our expectations, there was no significant three-way interaction.

5.3.4 Confidence

The ordinal logistic regression model revealed five main effects and an interaction. Table 4 shows the model coefficients and the odd ratios. However, due to involvement in interactions, main effects of tapping and landmark conditions will not be interpreted. The WM capacity of participants significantly predicted the confidence of participants (β = 1.71, p <.001). The odd's ratio indicates that as WM capacity increases, the odds of the participant to rate "high" confidence versus "medium" or "low" are 5.52 times greater. Similarly, in the second trial participants odds for "high" confidence was 2.07 times greater than in the first trial (β =0.74, p <.001). Finally, participants JRD error did significantly predict the odds of confidence ratings. With the JRD error increasing by 1 angular degree, the odds of a "high" confidence rating decreased by 0.009 (1-0.991). Finally, the model revealed that the effect of stress on participants confidence ratings depend on whether they learned local or global landmarks, β = 0.925, p < .001. In the tapping group, high confidence ratings become more likely in case participants judged between global landmarks as compared to local landmarks. The odds of participants rating "high" confidence were 2.52 times greater when they learned global landmarks in the tapping group than when they learned local landmarks in the tapping group.

Table 4: The table depicts the estimates of confidence ratings (β) and standard error (SE) of the ordered logistic regression.

				Odd ratios (95% CI)		
	β (SE)	t	p	OR	Lower	Upper
Tapping (high)	-1.060 (0.119)	-8.952	<.001	0.346	0.274	0.436
Landmark (global)	0.933 (0.117)	7.933	<.001	2.543	2.021	3.206
JRD Error (+1)	-0.009 (0.001)	-7.182	<.001	0.991	0.988	0.993
WM capacity (0.5)	1.709 (0.277)	6.173	<.001	5.524	3.221	9.540
Trial number (2)	0.727 (0.115)	6.301	<.001	2.070	1.652	2.597
Tapping x Landmark	0.925 (0.228)	4.050	<.001	2.522	1.614	3.952

OR = Proportional odds ratio, JRD = Judgment of relative directions, WM = Working memory

5.4 DISCUSSION

I studied the role of spatial WM on survey knowledge acquisition based on local and global landmark configurations during navigation in virtual cities. Our findings confirm our hypotheses in at least three ways. First, there was a global landmark advantage for survey knowledge acquisition. Second, the spatial concurrent task limited both navigation performance and survey knowledge acquisition, suggesting that the same WM resources are employed for these two tasks. Third, individual differences in WM capacity measured before navigation interacted with landmark type. In contrast to our expectation, however, this interaction showed the opposite effect. Participants' WM capacity was more strongly related to learning globally visible landmark configurations that were perceived simultaneously across the traversed environment than learning local landmark configurations that were viewed sequentially only when traveling nearby.

5.4.1 Memory for object-to-object relations

Our findings confirm the expected global landmark advantage for survey knowledge acquisition (hypothesis 1) and are consistent with prior research that found superior spatial memory for object-to-object relations when locations were presented simultaneously (rather than sequentially) for small (R. J. Allen, Baddeley, & Hitch, 2006; Blalock & Clegg, 2010; Lecerf & De Ribaupierre, 2005) and room-sized spaces (Lupo et al., 2018; Meilinger, Strickrodt, & Bülthoff, 2016; Ruotolo et al., 2012). The present study extends these prior findings to locations learned during navigation through large environments, such as cities, in VR. The results of Study II connect findings related to spatial WM across spatial scales and indicate the potential of VR for research that seeks to understand the mechanisms underlying navigation and survey knowledge acquisition. In comparison to our previous investigation (see Chapter 4), the present data demonstrate that the advantage of memorizing global landmarks in a common survey knowledge representation only occurs when the landmarks are located along the route rather than located at a distance.

5.4.2 Global landmarks and working memory

The present study found that participants' performance in global landmark learning benefited comparatively more from high WM capacities than in local landmark learning. This was not in accordance with hypothesis 3, which expected the a stronger positive relation between local landmark learning and WM capacity, because sequential learning should rely more on spatial working memory resources.

These results may be attributable to a floor effect for the measure of survey knowledge because I found poorer performance on the JRD tasks than most previous studies (e.g., Schinazi et al., 2013; Zhang et al., 2014; Huffman & Ekstrom, 2018). The missing positive relation between spatial WM capacity and local landmark learning could be explained by such a very low spatial learning performance of local landmarks. One possible explanation for this floor effect is that participants in the present study were only exposed to each environment for one navigation trial. Indeed, previous research has shown that survey knowledge assessed using JRDs improves significantly with increasing exposure to the environment (Zhang et al., 2014; Huffman & Ekstrom, 2018). However, some studies have found that participants do not significantly gain accuracy in survey knowledge over multiple trials along the same route (e.g., Schinazi et al., 2013). Another possible reason for the floor effect is too little training on the JRD task itself. For example, our results revealed a significant effect of trial number, although the two navigation trials employed different (counterbalanced) sets of landmarks. Future studies may need to include additional navigation trials to assess potential learning effects as well as extensive training on the JRD task (with feedback) to reduce general task difficulty. On the one hand, the positive relation between WM capacity and the performance in of mentally representing landmark configurations confirms findings from previous navigation research that have shown individual differences in the ability to acquire accurate metric knowledge about space (Schinazi et al., 2013; Ishikawa & Montello, 2006) and the importance of WM for survey knowledge acquisition (Hegarty et al., 2006; G. L. Allen et al., 1996; Münzer et al., 2006). On the other hand, these results extend prior knowledge by relating the individual differences to the kind of landmark information that is acquired.

5.4.3 Dual-task interference

In hypothesis 2, I expected that concurrent task demands disrupt the mental integration of landmarks in a survey representation via working memory. Our findings are consistent with this assumption and with prior research that demonstrated the detrimental effects of spatial interference tasks on navigators' abilities to encode spatial relations among landmarks during navigation in VR (Gras et al., 2013; Labate et al., 2014; Wen et al., 2013). This interference can be considered as an indication that both, a tapping task, and survey knowledge acquisition are drawing upon the same set of cognitive resources (Lindberg & Gärling, 1981). Furthermore, the group with the tapping task demonstrated a trend of higher SCL during navigation and significantly larger increases in self-reported distress (compared to the group without the tapping task) from the beginning to the end of the experiment. Both of these effects have been attributed to a large investment of cognitive resources via task demands in related work (Engström et al., 2005; Matthews et al., 2002). This tapping task can thus also be used to induce cognitive load for experimental purposes. However, participants may also experience a negative psychophysiological stress response and show decreased uncertainty about their spatial memory, which might not be a desired outcome. Future research could further disentangle the effects of concurrent (tapping) tasks on cognitive load and its effect on human emotions such as stress or confidence ratings.

In hypothesis 2, I also expected the tapping task to affect survey knowledge acquisition for different landmark configurations to the extent that their encoding relied on spatial WM, but our results did not reveal an interaction between tapping group and landmark type. Hence, it remains unclear whether the interference caused by the tapping task in this study was domain-general or specific to a particular WM subsystem. According to a domain-general interpretation of our results, the tapping task may have impaired several cognitive functions and redirected attentional resources away from the knowledge acquisition task (Barrouillet et al., 2011; Kane & Engle, 2003). This explanation is consistent with several studies that demonstrated interference across domains (e.g., Garden et al., 2002; Vergauwe, Barrouillet, & Camos, 2010). According to a domain-specific interpretation of the present results, survey knowledge acquisition for local and global landmark configurations may have relied on spatial WM in a similar manner despite differences in the visibility of the two types of landmarks. This interpretation is inconsistent with previous studies that have suggested that simultaneously visible objects require less processing in spatial WM than sequentially visible objects (e.g., Lecerf & De Ribaupierre, 2005).

5.4.4 Confidence level

Finally, the analysis of confidence ratings aimed to understand the factors that drive navigators certainty about their spatial memory. Our analysis has shown that the odds of rating a JRD trial with "high" confidence is significantly increasing with one's JRD performance, indicating that participants were able to judge the accuracy of their judgments. In addition, I could show that the effect structure of confidence ratings is very similar to that of the JRD error model, which also suggests that users can assess their own memory accuracy. For example, participants in the tapping group showed lower accuracy of survey knowledge and lower confidence. In contrast, participants with high WM capacity had increased memory accuracy and increased confidence. In general, our data confirmed prior findings that demonstrated a positive relation between spatial memory accuracy and confidence ratings (Stevens & Carlson, 2016). However, the confidence ratings of the present study did not involve a calibration procedure and therefore lack the possibility to identify under- or over-estimations. Future navigation research that is interested in participants ability to monitor their spatial knowledge needs to include calibration protocols that allow precise mapping of confidence ratings between participant.

Chapter 6

ANALYSES

6.1 THE EFFECT OF SIMULATOR SICKNESS

Navigation using virtual reality can cause simulator sickness (Dichgans & Brandt, 1978). Simulator sickness symptoms can be problematic because by increasing sweating it may confound the data on physiological arousal. In such cases, the skin conductance signal can no longer be unambiguously attributed to psychophysiological stress. Given these circumstances, I investigated the possible relationships between the stress manipulations and simulator symptoms (Section 6.1.1), between sickness ratings and both stress measures (Section 6.1.2), and finally the consistency among the stress measures (Section 6.2). Please note that due to substantial movement artifacts in the EDA signal, all data of five participants were excluded from the EDA analysis of Study I (n= 43, see Section 4.3.2.2) and all data of three participants were excluded from the EDA analysis of Study II (n= 48, see Section 5.2.6.5).

6.1.1 Did the stress treatments affect simulator sickness symptoms?

Participants in both studies showed moderate to high increases in nausea and disorientation symptoms due to the navigation task. An ANOVA was computed to analyze the effect of stress treatment (with / without) and study (I / II) on participants' simulator sickness symptoms. Figure 29 depicts the mean change in self-reported simulator sickess symptoms (nausea, oculomotor, and disorientation) separated by these factors. For the analysis, I used the total score of the sickness ratings (see Section 3.1.3). There was no significant main effect of stress treatments on participants' simulator sickness ratings ($F(88)= 1.33$, $p= .25$), indicating no difference between the with ($M= 0.39$, $SD= 0.80$) and without ($M= 0.613$, $SD= 1.00$) stress groups. There was also no significant main effect of the study, indicating no difference in participants' simulator sickness ratings between Study I ($M= 0.61$, $SD= 0.90$) and Study II, ($M= 0.42$, $SD= 0.91$; $F(88)= 0.98$,$p= .32$). However, the plot suggests a non-significant trend that participants in Study II reported less sickness symptoms than in Study I on average.

The results indicate that participants in the two groups, with or without stress treatment, showed similar levels of simulator sickness. Assuming that sickness symptoms can affect spatial learning, the present results indicate that any potential effect of sickness on learning should be similar for both groups.

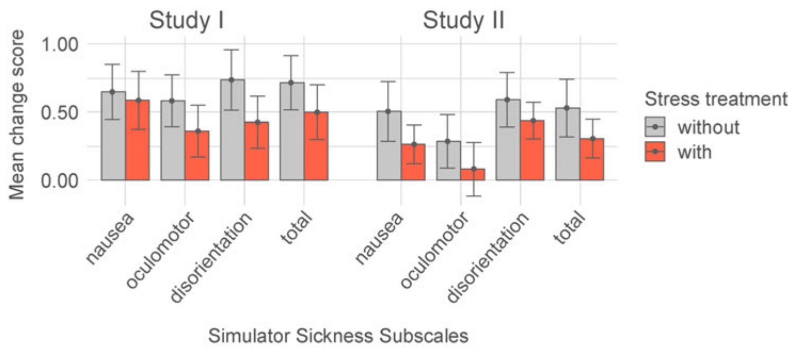


Figure 29: There was no significant difference in participants' simulator sickness ratings between the with and without stress groups. This result suggests that, even if sickness symptoms affected participants' stress ratings, these effects should not have significantly differed between the groups. The y-axis depicts the change between the pre- and post-task measurements. Error bars depict standard errors of each mean.

6.1.2 Correlation analysis

In this paragraph, stress measures (EDA and SSSQ) that were observed individually throughout the studies will be used to determine correlations with simulator sickness. Correlations between stress and simulator sickness measures could suggest that both measures influenced each other or partly measure the same construct. However, correlations need to be interpreted with caution because they do not allow for the inference of causal relations between variables. Pearson linear correlations were computed among the sickness scores (i.e., Simulator Sickness Questionnaire) and the stress measures (i.e., Short Stress State Questionnaire Subscales and EDA data). Figure A.2 contains the descriptive statistics of each variable's data. I computed two-tailed p-values using the Hmisc package in R that provides approximated p-values based on the t or F distribution (Frank & Harrell, 2019).

Figure 30 and Figure 31 show the correlation matrices of the observed sickness scores and stress ratings for each study.

In Study I, simulator sickness was positively correlated with self-reported distress, $r(43) = .65$, $p < .001$, and negatively correlated with self-reported engagement, $r(43) = -.35$, $p = .022$. This means that participants who reported more severe sickness symptoms also reported higher distress ratings and lower engagement ratings. Furthermore, there was a significant correlation of sickness ratings and Tonic SCL ($r(43) = -.33$, $p = .032$). However, participants' sickness ratings did correlate with self-reported worry ($r(43) = 0.23$, $p = .132$) and NS-SCR ($r(43) = -0.13$, $p = .398$).

In Study II, no significant correlations were found between simulator sickness and Tonic SCL ($r(48) = .06$, $p = .678$) or simulator sickness and NS-SCR ($r(48) = -.14$, $p = .349$). This suggests that, in

Study II, the EDA signal was not systematically confounded with noise that was been introduced by simulator sickness. Furthermore, participants' sickness symptoms were not correlated with self-reported distress (r(48) = -.18, p = .211), engagement (r(48) = -.25, p = .085), and worry (r(48) = -.08, p = .593).

6.1.3 Discussion

In summary, the present results suggest that, only for Study I, simulator sickness might have affected participants' stress levels and introduced a confound in our self-reported stress measure. However, given the present data, there is no way to rule out the alternative possibility that distress influenced the sickness ratings. Importantly, according to our prior analysis (see Figure 29), the severity of simulator sickness is similar for the with and without stress groups. In case there was an effect of sickness symptoms on the distress experience, it probably would have had a similar influence on the two experimental groups.

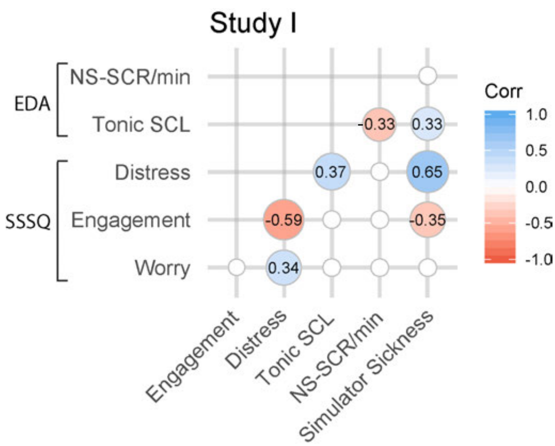


Figure 30: Correlations among participants' stress and simulator sickness scores from Study I (n = 43). Participants who reported more severe sickness symptoms also had increased tonic SCL and reported higher distress and lower engagement ratings. This suggests that in Study I, sickness had an impact on participants stress ratings and on their tonic SCL.

6.2 Consistency of stress measures

This subsection examines the possible correlations among the different stress measures (EDA and SSSQ). Consistency among these measures would suggest that they are related. Regarding the correlation between the two measures of electrodermal activity, I expect a positive correlation. Recent evidence has shown that the analysis of the frequency of non-specific responses (NS-SCRs) can be

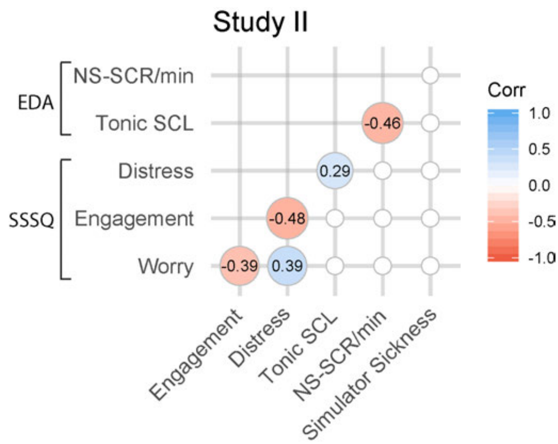


Figure 31: Correlations among participants' stress and simulator sickness scores from Study II (n = 48). Self-reported simulator sickness was not correlated with participants' ratings on the stress questionnaire (SSSQ). In contrast to Study I, the results of Study II indicate that EDA measures were not confounded by the effects of sickness symptoms.

used as a tonic EDA measure (tonic SCL). From that perspective, both measures similarly reflect the general presence of an arousing and negatively tuned psychophysiological activity (Boucsein, 2012; Posada-Quintero, Florian, Orjuela-Cañón, & Chon, 2018).

In the present data, there was a negative correlation between the tonic SCL and the NS-SCR measure, with $r(43) = -.33$, $p = .0295$ in Study I, and $r(48) = -.46$, $p < .001$ in Study II.

Regarding the correlation between self-reported measures and EDA I would also expect physiological arousal and psychological distress to be related (see, Section 2.6). According to the comprehensive stress theory of Matthews et al. (2013), the engagement and distress scales reflect, among other aspects, the physiological components of the stress response. More specifically, distress describes nervous and negative feelings that emerge from appraisals of high workload and high task demands(Matthews et al., 1999). Engagement is a mental state of interest and excitement regarding a task (Matthews et al., 1999). Both concepts are associated with with autonomic activation (Thayer, Takahashi, & Pauli, 1988; Matthews et al., 2002), and according to this perspective, I expect that both measures have a positive correlation with the electrodermal activity (EDA). However, prior empirical evidence in this area is mixed (Matthews et al., 2013; Acerbi et al., 2016; Thayer, 1989). Early studies (i.e., Thayer, 1978) demonstrated that energetic arousal and tense arousal (i.e., affective states that can be considered comparable to engagement and distress) correlated with skin conductance and various other measures of autonomic arousal (Matthews et al., 2013). To my knowledge, there is only one recent study that investigated the possible correlations among different physiological and self-reported stress measures. This study could not reproduce a correlation between skin conductance and self-reported psychological distress (Acerbi et al., 2016).

In both of the present studies, participants' distress ratings significantly correlated with tonic SCL, with $r(43) = .37$, $p = .016$ in Study I, and $r(48) = .29$, $p = .044$ in Study II. In contrast, participants' engagement ratings were not correlated with tonic SCL, with $r(43) = -.23$, $p = .139$ in Study I, and $r(48) = -.06$, $p = .693$ in Study II. Regarding the NS-SCR measure, no significant correlation was found in Study I and II for any scale of the self reported stress ratings (SSSQ). The moderate positive correlations between the distress ratings and tonic SCL for both studies suggest a physiological underpinning of the distress factor in the SSSQ and is consistent with the concepts of Matthews et al. (2013). However, the present data does not indicate a physiological underpinning for the engagement scale, a result which is not consistent with that theory. Additionally, the negative relation between the NS-SCRs and the tonic SCL is not in accordance with prior literature. With the present data, however, it would be mere speculation to draw conclusion about why these measures did not agree.

6.3 STATISTICAL COMPARISON OF STRESS MEASURES

In the main analyses of the two studies, I used time pressure and concurrent task group as the independent variables for explaining the JRD data. In the present section, I will provide insights into the power of other stress measurements from each study to explain the variance in spatial learning performance. Specifically, I will examine whether learning performance in the present studies (i.e., JRD error) is best explained by the experimental conditions (wit | without stressor), by the self-report data from the SSSQ, or by the EDA data. The SSSQ and EDA measures rely on different theories of stress and thus may assess different aspects of stress (see Section 2.6). In short, the SSSQ defines stress as a set of several psychological and physiological experiences (e.g., arousal, motivation, and intrusive thoughts) that represent a relationship between a person and the task demands (Matthews et al., 1999). Accordingly, the SSSQ measures stress by asking participants about their feelings and motivation regarding the current task demands (see Section 2.6.1). In contrast, EDA ties stress to a physiological response. While it is widely recognized that the EDA signal is driven by psychological processes, these processes cannot be reconstructed from the signal. For example, it is unclear if participants' were motivated or demotivated. By assessing which type of stress data fits our model best, we can better understand which dimensions of stress (i.e., motivation, intrusive thoughts, negative feelings, arousal) affect spatial knowledge acquisition.

Another objective of these analyses is to understand if the observed variables (i.e., EDA and SSSQ) fit the JRD data more accurately than the experimental manipulations (i.e., stress treatments). The reasoning behind this question resides on high individual differences in human responses to stressful events (Section 2.6). For example, psychological dimensions (e.g., motivation) or traits (e.g., personality) might moderate participants' stress responses. Hence, a participant assigned to the "without stress" group (e.g., no time pressure) may show a stronger stress response than a participant in the "with stress" group (e.g., time pressure) because he or she is unusually anxious in general. In such a case, observed stress measures may provide more precise predictions for spatial learning behavior (e.g., JRD data) than the stress manipulations. In the present section, I will use a model selection approach to investigate these possibilities for Study I and II. Each model was devised to represent a hypothesis from Section 6.3.1.1.

For each model selection, I will fit linear mixed effect models using the maximum likelihood method. For both studies, I will compare a baseline model without any stress data to three other models that use different stress variables. These stress variables correspond to (1) the experimental treatments, (2) the change scores of self-reported stress from the SSSQ (i.e., worry, engagement, distress), (3) or the change scores derived from the skin conductance recordings (i.e., tonic SCL and NS-SCRs/min). Table 5 shows the different factors that were used as explanatory variables in the candidate models.

Table 5: Overview of the different stress variables that were used as predictors in the candidate models.

Variable	n	stress predictor	Measure	scale
Baseline	0	None	–	–
Treatment	1	Time pressure (EXPI) Concurrent task (EXPII)	Treatments	Categorical (with | without)
SSSQ	3	Worry Engagement Stress	self-report	Continuous (numerical)
EDA	2	NS-SCRs/min Tonic SCL	Skin conductance	Continuous (numerical)

n = number of predictors; NS-SCRs/min = Number of non-specific short-term changes in the skin conductance response per minute. Tonic SCL = Level of activation in the sympathetic nervous system.

6.3.1 Comparison of statistical models

Because hypothesis testing is particularly limited in model selection (Royall, 1997), the present analysis does not rely on ordinary likelihood testing (like e.g., F-test or $\chi 2$) but relies on the information-theoretic paradigm (Burnham & Anderson, 2004). This paradigm is based on the tenets that every model is only an approximation of the unknown truth and that the best approach to judge the quality of a model is to estimate the information that is necessarily lost when the model is used to represent the truth (for more details about the Kullback–Leibler distance see Kullback & Leibler, 1951; Burnett, Summerskill, & Porter, 2004). Information-theoretic paradigms provide many advantages over classical null-hypothesis testing when more than one hypothesis is plausible and multiple predictors are considered interrelated (Johnson & Omland, 2004), such as in the present analysis. Accordingly, I followed the approach of Chamberlin (1965) and defined multiple theory-supported hypotheses (see Section 6.3.1.1) prior to computing any measures of model quality. Then, I compared the relative explanatory power using the AIC. The Akaike Information Criterion (AIC) is a well established information criterion that can help researchers to judge the relative amount of information that is lost by a given model when compared to another model. Thereby, the AIC provides information about which model has a better fit (i.e., higher likelihood; Akaike, 2011)). Because I compared models with different numbers of predictors, the AIC has the advantage (e.g., in contrast to R^2) of penalizing models for the number of free parameters (K). Specifically, I used a corrected version of (AICc) and thereby also accounted for over-fitting in small sample sizes (see Equation 3).

$$AICc = -2(loglikelihood) + 2K + (2K(K+1)/(n-K-1)) \tag{3}$$

From the AICc, we can compute the Δ AICc (see Wagenmakers & Farrell, 2004; Burnham & Anderson, 2004) that reflects the information loss of a model (which has a value bigger than 0) relative to the value from the best fit model (which has a Δ AICc of 0). According to Burnham and Anderson (2004), a Δ AICc of less than 2 (together with different log likelihood values) indicates strong evidence that the model is the most likely and represents the best fit of the data.

- Δ AICc < 2 = the model has substantial support.
- 3 > Δ AICc < 7 = less evidence for the model.
- Δ AICc > 10 = essentially no evidence.

Because it is difficult to judge the statistical importance of a difference in the Δ AICc, one can compute the weight of evidence in favor of the best model (Wagenmakers & Farrell, 2004). These weights denote the normalized probability that a model is the best fit (in terms of Kullback–Leibler discrepancy; Kullback & Leibler, 1951), where 1 is the most likely and 0 is the most unlikely. In the following analysis, we relied on Akaike weights to judge the relative power of model fits.

However, the AIC expresses only relative differences in the model fit. Along with these relative measures, researchers need to assess the absolute model fit (Nakagawa & Schielzeth, 2013). To do so, I used the marginal R^2 that quantifies the proportion of variance accounted for by the fixed effects and the conditional R^2 that quantifies the variance of both fixed and random effects considered together (Nakagawa & Schielzeth, 2013). Both measures of R^2 were computed in R using the MuMIn package (Barton, 2019).

6.3.1.1 Model hypotheses

For the present procedure, I formulated hypotheses about the relation between stress measures and spatial learning performance (JRD error).

- *h1:* Treatment versus Baseline – The stress treatment variables will provide more explanatory power for JRD error than our baseline model without any stress predictor. This hypothesis reflects two arguments. First, time pressure (Study I) or concurrent task load (Study II) should affect spatial learning. Second, stress should be determined by task demands. If the treatment model explains more variance than the other model candidates, it indicates that individual differences in the stress responses are not reflected in the JRD data as well as group differences.

- *h2:* EDA versus Baseline – Prior evidence has shown that high physiological arousal impairs WM functioning (Section 2.7.2) which should in turn impair spatial learning (Section 2.7.3). Therefore, we expect EDA measures (i.e., tonic SCL and NS-SCR/min) to outperform the Baseline model in explanatory power of the spatial learning performance.

- *h3:* EDA + SSSQ versus Treatment – Observed stress measures (i.e., SSSQ and EDA) predict the JRD data better than stress treatments (e.g., time pressure versus no time pressure). This advantage stems from high inter- and intra-individual differences in the human stress response that may only be accounted for through observational data at the individual level with baseline measurements.

- *h4:* EDA versus SSSQ – Self-report measures (i.e., SSSQ) suffer from limitations such as individual differences in understanding a question or biases towards responses that are socially desirable (Singleton Jr, Straits, Straits, & McAllister, 1988). In contrast, EDA cannot be consciously suppressed by humans and is not subject to desirability biases. Therefore, we expect EDA data to outperform SSSQ data in explanatory power of the JRD data.

In the following, we will evaluate these hypotheses in terms of the extent to which they are supported by the present data and best approximate reality.

6.3.1.2 Study I

In the main analysis of Study I, I employed ART ANOVAs for the analysis of JRD data (Section 4.2) because the assumption of homogeneity was not satisfied. However, the ART ANOVA is not able to regress continuous predictors as is needed to asses the individual stress measures (see Table 5). Using a log transformation, I could restore homogeneity across the categorical factors according to a Levene's test ($F = 2.2239$, $p = .092$). One shortcoming of log transformations is that we transform the scale of data in a nonlinear manner. Thus, the regression coefficients no longer represent predicted change in the raw dependent variable (i.e., JRD error) per unit of change in the independent variable (e.g., 1 unit of mean worry ratings does not correspond to 1 degree of JRD error anymore). After log transformation, the interpretation of effect sizes is therefore less informative and can be misleading. Furthermore, after a log transformation, models from Study I cannot be compared to models from Study II. However, in the present model selection analysis, these aspects are not of primary interest. Equation (4) shows the common structure of the regression model candidates of Study I plus a placeholder for the stress variable that varied between the models.

$$\begin{aligned} &\mathrm{JRD\ error} \sim \mathrm{landmark\ type} + [\mathrm{stress\ variable(s)}] + \\ &(1 \mid \mathrm{participant}) \end{aligned} \tag{4}$$

These model comparisons indicate that the treatment model based on the experimental manipulations provided the most likely model structure (Δ AICc = 0) with a weight of .52. However, the baseline model , with a Δ AICc of 1.25 and a weight of 0.28, was also supported. In direct comparison with the baseline model, the treatment model shows a relatively poor weights ratio. The treatment model is only 1.86 times more likely to be the best model than the baseline model. This weights ratio reflects a normalized probability of 65%. A closer examination of the fit according to log-likelihood (LL) is important because, if the LLs of both models are essentially the same, then the small Δ AICc reflects the additional parameter instead of additional explanatory power (Burnham & Anderson, 2002). The difference between the baseline model (LL

Table 6: The treatment model with a categorical stress variable has the smallest AICc value and provided the most likely model structure with a weight of .52. The baseline model has a weight of 0.23 and a Δ AICc smaller than 2, indicating support for that model to be as likely as the treatment model. Surprisingly, the models that included the individual data (EDA and SSQ) did not have strong support.

Model	K	AICc	Δ AICc	Weight	LL	$\mathcal{R}^2$m	$\mathcal{R}^2$c
Baseline	4	138.94	1.25	.28	-65.21	0.0237	0.2711
Treatment	6	137.69	0.00	.52	-62.29	0.1010	0.2913
EDA	7	141.51	3.82	.08	-63.00	0.0635	0.3104
SSSQ	6	140.58	2.89	.12	-63.73	0.0870	0.2716

= -65.21) and the treatment model (LL = -62.29) is moderate, suggesting that the observed change in information criteria did not emerge due to the addition of predictors. To sum up, according to the AICc, the treatment model is the most likely, however, we cannot claim with high certainty (weight of 0.52) that the treatment model is a better fit than the baseline model.

In Study I, all of the models had a poor absolute fit. The fixed effects (R^2_m) of the baseline model accounted for 2.37% of the variance. In comparison, the treatment model (best fit) accounted for 10.1% of the variance. This is (relatively) more than 3 times the explained variance of the baseline model. When random intercepts and slopes were included, the absolute fit increased to 27.11% for the baseline model, and increased to 29.13% for the treatment model. Lower absolute fits are typical for behavioral data and, in the present study, reflect the high variance in JRD error (SD = 47.6, IQR = 13.8 – 67.5). Importantly, poor absolute fits do not interfere with the validity of the model term coefficients that express variations in the dependent variables due to changes in the independent variable.

6.3.1.3 Study II

For the model comparison of Study II, I employed the same linear mixed effects model structure as in the main analysis (see Section 5.3). Due to missing values in the EDA data (see Section 5.2), all of these models were fit to a subset of 1092 observations (out of 1224 total). Equation (5) shows the common structure of the model candidates in Study II and includes a placeholder for the stress variable(s). For each model candidate of Study II, the baseline model is extended by the stress variable(s) displayed in Table 5.

$$\text{JRD error} \sim \text{landmark type} * \text{WMcapacity} + \text{trial number} + [\text{stress variable(s)}] + (1 \mid \text{triple}) + (1 + \text{landmark type} \mid \text{participant}) \quad (5)$$

The results of the model comparison (see Table 7) show that the SSSQ model has the smallest AICc value and provided the most likely fit with a weight of 0.77. The treatment model has a weight of 0.23 and a Δ AICc bigger than 2, indicating only little support for that model. All other models have no substantial support. Interestingly, the model based on the EDA data performed worst with the highest amount of information deficit (13.69) compared to the best fit.

Table 7: Results of the model comparison procedure of Study II

Model	K	AICc	Δ AICc	Weight	LL	$\mathcal{R}^2$m	$\mathcal{R}^2$c
Baseline	10	11373.26	10.41	.00	-5676.53	0.1112	0.24233
Treatment	11	11365.29	2.43	.23	-5671.52	0.1363	0.24233
SSSQ	13	11362.86	0.00	.77	-5668.26	0.1507	0.24241
EDA	10	11376.54	13.69	.00	-5676.13	0.1132	0.24332

Surprisingly, the comparison procedure revealed that the three subscales of the SSSQ provided the best fit to the data (Δ AICc = 0). However, it also seems that the treatment model did provide a better fit to the data (Δ AICc = 2.43) than the baseline model without any stress predictor (Δ AICc = 10.41). However, in direct comparison with the treatment model, the high probability of the SSSQ model (0.77) and the Δ AICc of 2.43 (above 2) for the treatment model indicated a significantly better performance of the SSSQ model. The weights ratio for the best (SSSQ model) compared to the second best (treatment model) is 3.35, meaning that the SSSQ model is 3.35 times more likely than the treatment model.

In contrast to the SSSQ model, the EDA model performed poorly in explaining JRD errors and did not provide a better fit than the baseline model without any stress predictor (Δ AICc 23.03). Hence, a person with higher increases in NS-SCRs or tonic SCL (compared to a baseline measure) did not systematically perform worse in the JRD task than someone with lower NS-SCRs or tonic SCL. For Study II, we can say that there was no gain from including participants' EDA data in the model for explaining participants' spatial learning performance. However, there was an information gain attributable to including the SSSQ data.

Before drawing inferences from the SSSQ model (best fit), it has to be noted that all of the models had quite a poor absolute fit in Study II. While the fixed effects (R^2_m) of the baseline model accounted for 11.12% of the variance, the SSSQ model (best fit) accounted for 15.07% of the variance. When random intercepts and slopes were included, the absolute fit increased to 24.23% for the baseline model and increased to 24.24% for the SSSQ model.

Taken together, the SSSQ model was the best fit according to the AIC model selection procedure (evidence ratio 0.77). Table 8 shows the coefficients of the SSSQ model terms with the distress, engagement, and worry subscales as explanatory variables. Interestingly, participants' JRD errors did significantly increase (by 12 angular degrees) with 1 unit increase in distress ratings, $t(46.773) = 3.8$, $p < .0001$. In contrast, participants' JRD errors significantly decreased (by 9 angular degrees) with 1 unit increase in worry ratings, $t(46.366) = -2.65$, $p = .011$.

Table 8: The model terms of the SSSQ model show that with increasing distress ratings participants showed worse accuracy of survey knowledge. Conversely, with increasing worry ratings participants showed better accuracy of survey knowledge. This result support the notion to include cognitive and motivational aspects of the stress dimension to better understand the multifaceted effects that stressful contexts may have on spatial behavior.

	β	Std. Error	df	t value	p
Intercept	43.069	4.338	48.518	9.927	2.86e-13 ***
LM (global)	-17.111	3.814	25.091	-4.486	.0001 ***
WM capacity (0.5)	-61.536	13.099	47.254	-4.698	< .0001 ***
trial number (2)	-14.252	3.673	48.037	-3.880	.0003 ***
distress (0.5)	12.006	3.154	46.773	3.807	.0004 ***
engagement (0.5)	-1.344	2.725	48.648	-0.493	.6240
worry (0.5)	-9.270	3.502	46.366	-2.647	.0111 *
LM x WM capacity	-46.931	21.372	46.051	-2.196	.0332 *

6.3.2 Discussion

This finding supports our expectation (h1) that, by knowing task demands alone (i.e., the experimental treatments), we can predict learning outcomes in VR navigation. The evidence was especially convincing in Study I for which the treatment model provided the most likely fit. The quality of the treatment model to explain data of Study II also support this hypothesis. Even though these models did not include any observed measure that indicated the stress state of an individual, it significantly improved the explanatory power of the baseline model by only considering the contextual information (e.g., with or without time pressure).

Finally, the results of the model comparison contradict hypothesis (h2) that stated that the physiological components (i.e., tonic SCL and NS-SCR/min) of stress are better predictors of spatial learning performance than no predictor (baseline model). The fact that the EDA model was consistently the worst performing model contradicts this hypothesis. This might be explained by the potential losses in data quality that were introduced by simulator sickness. At least in Study I correlation analysis (Section 6.1) has suggested that simulator sickness might have introduced noise and thus affected the validity of the EDA signal. Although I could decrease the likelihood of confounding variables by providing a laboratory setup, sweat production caused by simulator sickness might have affected the EDA response and decreased its usefulness as a proxy for stress.

Another possible reason for decreased validity of the EDA measure as an indicator of stress is that EDA measurements were not event-related (Section 3.3.2.4). In contrast to an event-related approach, the primary purpose of the present research was to assess the stress level of participants for a period of several minutes during navigation. Therefore, I normalized and averaged the EDA signal over dynamic time windows of 2 or more minutes (e.g., the average number of NS-SCRs). However, this process might have produced inconsistencies in the results. For example, in Study I, participants in the time pressure group showed an increased frequency of NS-SCR/min but no increase in tonic SCL. We found the opposite pattern in Study II because participants in the spatial tapping group showed an increase in tonic SCL but no increase in the frequency of NS-SCR/min. On the one hand, averaging the EDA signal over a time window of 2 or more minutes seems to be inconclusive in terms of both NS-SCR/min and tonic SCL. On the other hand, tonic SCL showed a similar response to our stress treatments than participants' distress ratings in both studies. Also, positive correlations between tonic SCL and participants' distress ratings indicate a relation. Also this is somewhat speculative, if we take the distress scale as a kind of ground truth to evaluate the tonic SCL, then the behavior of the tonic SCL turns out as expected. However, with respect to the bad performance of the EDA models, this reasoning has no substantial support in the present data. Rather, regarding the good performance of the SSSQ model in Study II, future research might consider using self-report (e.g., the SSSQ) data to investigate the multifaceted effects of stress on spatial memory.

The good performance of the SSSQ model as compared to the EDA model might also indicate that survey knowledge impairments are less driven by physiological processes and more driven by a multitude of psychological dimensions that emerge in combination with task demands (Matthews et al., 1999). In support of this hypothesis are also the coefficients of the SSSQ model for Study II that show a divergent influence of the distress and the worry factor on the JRD data. In contrast, using the tonic SCL as sole stress predictor subsumes these contrasting influences in a unitary concept like physiological arousal. Hence, researchers loose information about important motivational and cognitive drivers of stressful behavior. Regarding the theoretical underpinnings of the SSSQ, future research in navigation and spatial cognition may want to rely on transactional perspectives that conceptualize stress as relation between the environment (i.e., context, task) and a person's continuous attempts to understand and cope with these environmental demands (see transactional theory of stress by Lazarus and Folkman, 1984).

Regarding hypothesis (h3), there is no general advantage in the explanatory power of observed measures (i.e., SSSQ and EDA) as compared to the stress treatments in the present data. The analysis of both studies showed mixed results concerning the self-reported and the physiological measures and indicated that each measure needs to be considered individually. These individual considerations will follow along with discussing hypothesis h4.

According to hypothesis (h4), EDA measures were poorer predictors of spatial learning performance than SSSQ measures. This is surprising given the frequently expressed limitations regarding the "subjectivity" of self-report measures (Singleton Jr et al., 1988) and the excitement about "objective" measures such as EDA. Indeed, the present results reflect that the psychological and self-reported dimensions of stress have a better explanatory power for spatial learning performance during navigation than the physiological state of a person. This is also supported by the significant model terms of distress and worry on spatial learning performance from the SSSQ model.

6.4 THE EFFECT OF GENDER

Navigation is one of the cognitive abilities that is most consistently affected by gender differences regardless of the different cultures (Silverman, Choi, & Peters, 2007). Specifically, much research has found significant differences between females and males in the ability to acquire survey knowledge (e.g., Castelli et al., 2008; Montello, Lovelace, Golledge, & Self, 1999). One explanation for these findings is that female and male navigators differ in their strategies how spatial information about the environment is used for orientation and for spatial learning (Harris, Scheuringer, & Pletzer, 2019; Lawton, 1994). For example, when participants are asked to verbally describe a route they have just traveled, men rely more on allocentric terms and metrical descriptions (e.g., take the road south in 100 meter), while women rely more on egocentric terms and landmarks (e.g., turn right after the restaurant Lawton, 2001). Importantly, when men and women report about how they acquire knowledge about space, men report taking shortcuts and looking for distal landmarks to orient while women indicate to typically follow well-learned routes using local landmarks (Lawton, 2001, 1994; Coluccia & Louse, 2004). Another factor that determines differences between male and female navigation abilities might be because males often show larger WM capacities. For example, (Coluccia & Louse, 2004) proposed that gender differences in orientation ability may primarily occur when a task poses strong demands on visuo-spatial WM.

Padilla et al. (2017) could empirically demonstrate that males have superior performance compared to females when navigating with global landmarks in small-scale spaces. However, this advantage diminished in a comparable, but larger environment (Padilla et al., 2017). To understand the influence of gender in the present spatial memory data, this analysis compares participants JRD performance of males and females along landmark condition (local / global) and stress (with / without). According to the findings reported above, I formulated hypotheses about the relation between gender and spatial learning performance (JRD error) of local and global landmark configurations.

- *h1:* Males show more accurate survey knowledge than females.
- *h2:* The accuracy of survey knowledge increases for global landmark configurations. This increase is greater for males than for females.
- *h3:* The accuracy of survey knowledge decreases under concurrent task load. This decrease is greater for males than for females.

The data of Study I violated homogeneity of variance (see Section 4.2.6). Hence, I also employed the ART ANOVA for the gender analysis of this data. In addition to comparing gender performance when judging spatial relations between local (without global) and global (without local) landmarks, I will examine performance when participants were pointing to global landmarks that were not highlighted (see condition (c) in Figure 12). This analysis will help to understand if the spontaneous use of global landmarks is different between males and females. To examine the performance of survey knowledge from these landmarks, a mixed factorial ANOVA with gender (female / male) and time pressure (with / without) as between-subjects factors was computed for the mean absolute angular error of JRDs.

For Study II, the gender effect was analyzed using the linear mixed effects model from Section 5.2.6, however, the original model was extended by a gender factor. Because prior literature has indicated a strong relation between WM capacity and gender, I checked for collinearity. A regression model with collinear explanatory variable may not give valid results about any individual variable. Typically, males score higher on spatial WM spans than females (Geiger & Litwiller, 2005). However, in the spatial WM span task of Study II, males did not score higher ($M = 0.69$) than females ($M = 0.64$) on average ($t = 1.11$, $df = 48.994$, p-value $= .274$). Also, variance inflation factors of the gender ($vif = 1.05$) and WM capacity ($vif = 2.74$)

model terms were each lower than 4 (Zuur, Ieno, & Elphick, 2010). Hence, the data shows no indication for collinearity. Therefore, I did not exclude WM capacity as explanatory variable from the gender regression model. However, because the full model including the gender predictor did not converge, I successively excluded random slopes and then random intercepts. The first model that converged was the full model without the by-participant slope (i.e., landmark type as random slope). Equation (6) shows the model structure for the analysis of Study II.

$$\begin{aligned} &\text{JRD error} \sim \text{landmark type} * \text{spatial tapping} * \text{WMC} \\ &* \text{gender} + \text{trial number} + (1 \mid \text{triple}) + \\ &(1 \mid \text{participant}) \end{aligned} \tag{6}$$

6.4.1 Study I

In Study I, the ART ANOVA revealed that the main effect for sex was significant $F(1,44) = 6.49$, $p = .014$. Thus, men showed increased accuracy in the JRD task ($M = 39.8$, $SD = 43.0$) compared to women ($M = 50.4$, $SD = 45.8$). However, there was no interaction between gender and memory of local (without global) or global (without local) landmarks $F(1,44) = 0.28$, $p = .597$. Similarly, I could not observe an interaction between gender and stress group $F(1,44) = 0.76$, $p = .389$. Figure 32 shows the mean values of each cell and the 95% confidence intervals.

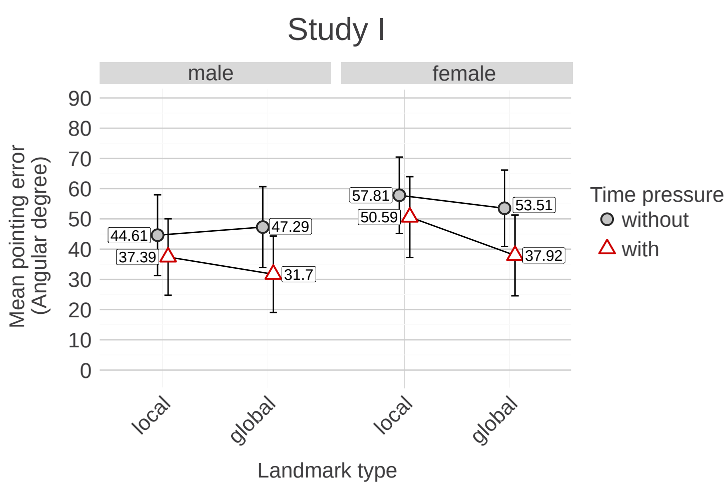


Figure 32: Absolute JRD error for males and females. Dots represent means and error bars depict 95% confidence intervals.

The mixed factorial ANOVA revealed no significant difference between males ($M = 59.9$) and females ($M = 70.3$) in the directional judgments towards global landmarks $F(44)=2.62$, $p = .113$

that were implicitly learned. This indicates no effect of gender on spontaneous usage global landmarks for spatial learning in the present study. Furthermore, males and females had similar JRD performance in the with and the without time pressure condition $F(44)= 0.0653$, $p = .799$.

6.4.2 Study II

In Study II, the linear mixed model (see Equation 6) with orthogonal contrasts revealed that males had greater survey knowledge accuracy ($M = 52.1$, $SE = 3.3$) than females ($M = 60.3$, $SE = 3.2$) in Study II, however, this difference was not significant ($\beta = 8.2$, $SE = 4.5$, $t(42.86) = 1.85$, $p = .071$). Furthermore, males were equally accurate than females when judging directions between local or global landmarks ($\beta = 7.8$, $SE = 7.2$, $t(41.39) = 1.1$, $p = .286$) or when learning with or without spatial tapping ($\beta = -8.18$, $SE = 8.9$, $t(42.88) = -0.92$, $p = .363$). Finally, there was also no significant interaction between WM capacity and gender ($\beta = 22.85$, $SE = 28.1$, $t(42.9) = -0.81$, $p = .421$). Figure 33 shows the estimated marginal means and 95% confidence intervals for all the factor combinations of gender, spatial tapping, and landmark type.

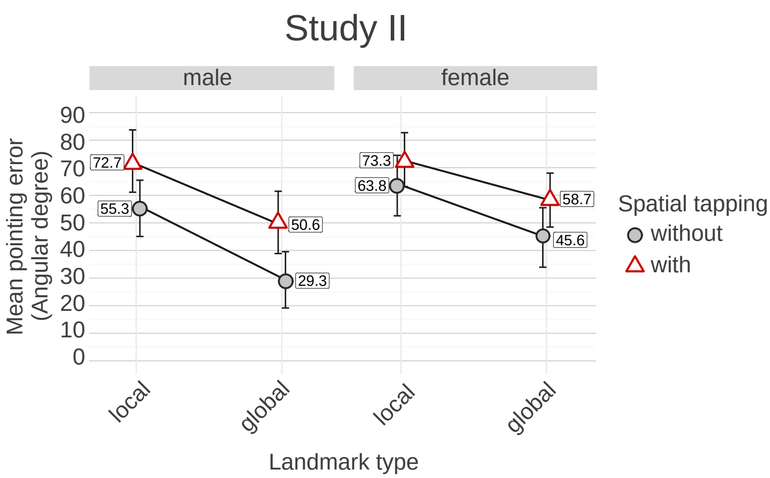


Figure 33: Absolute JRD error for males and females. Dots represent estimated means and error bars depict 95% confidence intervals.

A post-hoc model comparison procedure reveled that the present data is most likely explained by a model that includes gender as a main-effect. Table 9 shows the results of the comparison between a model without gender variable (Without), a model with the gender variable as main-effect (+Gender), and a model with the gender variable interacting with the other variables (*Gender). Equation 6 shows the model structure of the *Gender model. The +Gender model has the smallest AICc value and provided the most likely model with a weight of 0.75. The Without model has a weight of 0.23 and a Δ AICc bigger than 2, indicating only little support for that model. The +Gender model is 3.26 times more likely to be the most likely model than the Without model. Finally, the *Gender model has no substantial support.

Table 9: The results of the model comparison showed that including a gender main effect into our original model from Study II (see Equation 6) is the most likely model that best fits the JRD data.

Model	K	AICc	Δ AICc	Weight	LL	$\mathcal{R}^2$m	$\mathcal{R}^2$c
Without	12	12730.04	2.36	.23	-6354.08	0.1397	0.2125
+Gender	13	12732.41	0.00	.75	-6351.87	0.1484	0.2127
*Gender	20	12736.98	6.94	.02	-6348.14	0.1564	0.2160

6.4.3 Discussion

The gender analysis confirmed our hypothesis 1 that males show increased accuracy of survey knowledge than females. This finding is in accordance with much previous research (e.g., Castelli et al., 2008; Montello et al., 1999) and implies that the investigation of gender effects together with spatial abilities can increase our understanding of large-scale spatial learning processes.

Contrary to hypothesis 2 and against some prior indications of a male preference for global orientation (Lawton, 1994; Coluccia & Louse, 2004; Lawton, 2001), the present empirical work did not find support for a moderating role of gender in the use of local or global landmarks for the acquisition of survey knowledge. This might be explained by the fact that participants have navigated large-scale environments in the present study. Previous evidence showed that global landmarks improved navigation performance of men compared to performance of women only when navigating in small-scale environments (Padilla et al., 2017). The relevance of scale when navigators rely on global landmarks might be explained by the fact that with increasing distance, landmarks loose their ability to provide precise location information. For example, in the study of (Padilla et al., 2017), precise memory of relative locations was required to find the hidden goal in the Morris water maze task. In the present study, precise memory of relative locations was required to integrate landmarks into a survey representation. The present results imply that the benefits of distal landmarks to provide directional information is used by men and women alike for survey knowledge acquisition. Future research should investigate the role of gender effects when the task requires the acquisition of route knowledge.

Contrary to hypothesis 3, the present results show no differences in the effect of task load on spatial learning between males and females. This finding does not support the proposal that gender differences are strongly determined by a task's demands on working memory (Coluccia & Louse, 2004). To address the relationship between gender and WM factors in the context of landmark learning, future research may want to further investigate differences in implicitly attending global landmarks under different concurrent task demands (e.g. in the Morris water maze paradigm).

Chapter 7

GENERAL DISCUSSION

The main goal of the thesis was to examine the potential of simultaneously visible global landmarks for facilitating the acquisition of survey knowledge during navigation under stress. Therefore, I assessed the accuracy with which people integrated multiple local or global landmarks into one coherent mental representation during navigation with and without stress. The present chapter critically discusses my findings presented in Chapter 4 and Chapter 5 in the context of the state of the art and addresses some limitations of my research approach. I organize the discussion in terms of the main research questions that were defined in Section 1.2.

7.1 HOW ACCURATE IS THE ACQUISITION OF SURVEY KNOWLEDGE FROM LOCAL AND GLOBAL LANDMARKS?

This thesis provides evidence for a spatial learning advantage of simultaneously visible global landmarks compared to landmarks that are only locally visible for a pedestrian navigating in a virtual environment. This is in accordance with many studies from the spatial cognition literature (Colle & Reid, 1998; Weisberg et al., 2014; Wang & Brockmole, 2003; Ruotolo et al., 2012; Meilinger, Strickrodt, & Bülthoff, 2016; H. Li et al., 2016). However, the present findings extend previous research by demonstrating that higher accuracy for survey knowledge of global landmarks may be evident when the landmarks are located along the route but not when they are seen from a distance by the pedestrian wayfinder.

The advantage of global landmarks along the route over distant global landmarks is consistent with the theory of spatial learning described by Siegel and White (1975). Following this perspective, landmarks along the traveled route and landmarks at decision points are the building blocks of spatial memory of large-scale environments during navigation. Accordingly, there is some evidence that route knowledge improves when landmarks are located along the route (Lovelace et al., 1999) or at decision points (Jansen-Osmann & Berendt, 2002; Denis et al., 1999). Participants in Study II who traveled to the locations of global landmarks were able to encode inter-landmark relations (i.e., distances and directions) via simultaneously viewing them and via learning mechanisms such as route learning and path integration. This combination might have led to more accurate survey knowledge for global landmarks than for local landmarks that could not be viewed simultaneously. Conversely, in Study I, both, route knowledge and path integration may have been less helpful for learning global landmarks that could only be viewed at a distance. One explanation could be that navigators were required to infer landmark distances by means of retinal motion cues (e.g., the velocity at which different objects moved across the retina) and derive inter-object relations using such inferences. Because the accuracy of estimating the absolute distances of objects diminishes with distance (Cutting & Vishton, 1995), survey representations for distant objects may also be less precise than survey representations for close objects.

Notably, this interpretation conflicts with the finding that global landmarks were not learned implicitly in Study I. In two conditions of Study I (see conditions a and c in Figure 12), participants were instructed to learn the locations of only the local landmarks along the route but also had either no or two global landmarks located at a distance. In this case, participants did not benefit from the presence of global landmarks for constructing a survey representation of local landmark configurations, although these participants could have relied on route knowledge and/or path integration to mentally integrate local landmarks into a survey representation. This finding implies that people do not implicitly rely on global landmarks for the representation of local information in a survey representation. Similarly, Steck and Mallot (2000) found that only some individuals use distant global landmarks during goal-directed navigation in VR and that these individuals do not consistently rely on distant global landmarks along the entire path. Besides landmark usage that varies between and within individuals (Steck & Mallot, 2000), the spontaneous use of global landmarks may also rely on gender (Lin et al., 2012), saliency (Sorrows & Hirtle, 1999), or orientation strategies (Hurlebaus, Basten, Mallot, & Wiener, 2008). However, in Study I, I did not find any relationship between the accuracy of survey representations and participants' self-reported navigation strategies (Münzer & Hölscher, 2011). On the one hand, this may suggest that participants' strategies and preferences for mentally representing an environment had no impact on spatial memory of landmark configurations. On the other hand, this null effect could be attributed to the fact that, in Study I, assessment of navigation strategies was based on self-reports and people often do not know exactly how they perform a task or why they performed a task in a particular kind of way. Contrary to this interpretation is the agreement in the collected data between confidence ratings and JRD performance, which indicates that participants did have a good sense about how well they performed the spatial learning task.

Another possible explanation for the advantage of global landmarks along the route in terms of spatial learning can be named "the goal effect". In Steck and Mallot (2000), participants demonstrated a preference for memorizing landmarks (i.e., either local or global) during navigation that could be easily associated with previously learned goal locations. For example, a mountain ridge was remembered better when it was located in the same direction as participants' goal location. In the present study, this goal effect may have provided a learning advantage particularly for those global landmarks that were along the route. When located along the route and globally visible, participants could associate the remote locations with the route to be traveled and hence use them as intermediate goal locations. Importantly, in the local landmark condition, there was no such salient global landmark that could be used as intermediate goal location.

7.2 WHAT IS THE ROLE OF INDIVIDUAL SPATIAL ABILITIES DURING SURVEY KNOWLEDGE ACQUISITION FOR LOCAL AND GLOBAL LANDMARK CONFIGURATIONS?

One of the most surprising findings from the present thesis is that the advantage of global landmarks for survey knowledge acquisition is observed only for participants with higher working memory (WM) capacity as shown in Study II. This finding is in accordance with prior evidence that individual differences in WM capacity are associated with the ability to acquire survey knowledge (e.g., Münzer et al., 2006). However, we did not find a relationship between local landmark learning and WM capacity.

One way to interpret these results is that learning global landmark configurations relies more strongly on WM capacity than learning local landmark configurations. This interpretation conflicts with prior evidence that has demonstrated an encoding advantage for simultaneously visible objects compared to sequentially visible objects (Lecerf & De Ribaupierre, 2005; Jiang et al., 2000; Blalock & Clegg, 2010; Lupo et al., 2018). However, Yamamoto and Shelton (2009) showed that sequential presentation can lead to similar, even slightly better, survey knowledge than simultaneous presentation. The authors interpret this finding as evidence that sequential presentation required longer periods of attention than simultaneous presentation. However, in the studies of this thesis, the sequential presentation of landmarks may not have led to an advantage over simultaneous presentation because participants were able to view global landmarks over longer periods of time than local landmarks.

Another possible interpretation of the difference between learning local and global landmarks in terms of their relationship with WM capacity is that local landmark configurations were too difficult to learn in the present study. This floor effect explanation is plausible because of the generally poor performance in the local landmark condition compared to previous studies (Schinazi et al., 2013; Zhang et al., 2014; Huffman & Ekstrom, 2018), even among participants with high WM capacity. Consistent with this interpretation is prior evidence that survey knowledge acquisition in city-scale spaces is generally a difficult task and involves the active allocation of cognitive resources in WM (Münzer et al., 2006; Wen et al., 2011; Chrastil & Warren, 2013; G. L. Allen, 1999). The difficulty of the spatial learning task in the present study may have been exacerbated by the use of VR because participants needed to rely solely on visual information to maintain their orientation (Hegarty et al., 2006) and may have experienced simulator sickness. In these circumstances, it is possible that participants with high WM capacity were still unable to construct accurate survey knowledge from local landmarks. However, the present data does not allow me to disentangle these two possibilities with empirical evidence.

One way to overcome this limitation in future research would be to minimize simulator sickness symptoms by, for example, using more extensive habituation procedures before data collection in VR (Howarth & Hodder, 2008). Prior research demonstrated that sickness scores decreased over participants' first four sessions in VR and then stabilized (Kennedy et al., 1993). However, multiple habituation sessions may involve considerable time and costs. Alternatively, future research could also consider studying local and global landmark learning in real environments when participants can use internal cues (e.g., kinesthetic and vestibular information) to support visual encoding in the formation of survey knowledge.

In contrast to the findings of this thesis, prior research that was conducted in room-sized spaces (Ruotolo et al., 2012; Meilinger, Strickrodt, & Bülthoff, 2016; Lupo et al., 2018) demonstrated the advantages of simultaneously visible objects for spatial learning without assessing participants' spatial abilities. This implies that simultaneously visible objects lead to more accurate survey knowledge than sequentially visible objects independent of peoples' spatial abilities. Conversely, the present data implies that the benefits of global landmarks for spatial learning of large-scale spaces depend on the spatial abilities (i.e., WM capacity) of individuals. In my view, this conflict between prior research and the present findings highlights the relevance of spatial scale and learning perspective to understand individual differences in spatial memory systems.

The importance of the learning perspective for survey knowledge acquisition has been indicated by prior research when map learning was compared to learning from navigating an environment in first-person perspective (Thorndyke & Hayes-Roth, 1982; Ishikawa et al., 2008; Zhang et al., 2014; Fields & Shelton, 2006). These studies have demonstrated that participants who learned environments from maps mentally represent inter-object relations faster and with less cognitive effort than participants who learned such relations from navigating in first-person perspective. Importantly, participants in the present studies could not use their navigation aid to view inter-landmark relations from a bird's eye perspective, because landmarks were not displayed on the map and map-scale was very large (i.e., only a small proportion of the environment was displayed). Rather, participants of the present studies needed to attend landmarks from first-person perspective in order to acquire survey knowledge of the virtual environment.

Similarly to learning from a map, participants in the simultaneous encoding condition of the studies mentioned above (Ruotolo et al., 2012; Meilinger, Strickrodt, & Bülthoff, 2016; Lupo et al., 2018) could oversee the locations of all objects from a birds-eye perspective. In contrast, participants in the present studies' simultaneous conditions could view multiple global landmarks at a glance, but because some of these landmarks were visible at a distance, they mainly conveyed directional information. To encode the relative locations of global landmarks in large-scale spaces, participants needed to infer their positions from optic flow or rely on path integration. Both of these mechanisms introduce inaccuracies in survey knowledge when compared to learning a layout from a bird's eye view (Hegarty et al., 2006; Fields & Shelton, 2006; Cutting & Vishton, 1995). Even though global landmarks were simultaneously visible, it is possible that their encoding from first-person perspective introduced higher demands on participants' WM resources. This reasoning is in accordance with the findings of Fields and Shelton (2006) who demonstrated that survey knowledge acquisition from first-person perspective as compared to map learning puts additional cognitive demands on participants. With respect to this evidence, the present data implies that the benefits of simultaneous visibility of landmarks for spatial learning should be weaker from first-person perspective than from bird's eye perspective.

The present studies provide first evidence that ties WM capacity to the encoding and learning of local and global landmarks from navigating in first-person perspective. During pedestrian navigation, learning perspective is constantly changing and spatial abilities may play a more important role than during learning from a bird's eye perspective or from a fixed viewpoint (e.g., Fields & Shelton, 2006). Future research that investigates the cognitive mechanisms that are required for mentally integrating local and global landmarks into a survey representation should therefore extend data collection about the different kinds of WM capacities (e.g., visual, spatial, and verbal) that may support learning of different types of landmarks. To make sure that the assessment of spatial memory has enough statistical power (e.g., when using the JRD task), future research should find appropriate means to reduce simulator sickness in VR and also consider to decrease the difficulty of the spatial learning task (e.g., by reducing the number of landmarks).

7.3 HOW DO CONTEXTUAL STRESSORS INTERFERE WITH SUCCESSFUL SURVEY KNOWLEDGE ACQUISITION FOR LOCAL AND GLOBAL LANDMARKS?

Previous research has provided mixed evidence about the relationship between stress and spatial learning (Duncko et al., 2007; Evans et al., 1984; Richardson et al., 1999). The present empirical work suggests that different contextual stressors may differ as to whether they affect survey knowledge acquisition. Specifically, the present results imply that stress-induced impairments of survey knowledge are strongly related to impaired WM. Participants in the time pressure condition of Study I did not show any indications of WM impairments. Accordingly, they performed similarly on a survey knowledge task as participants in the condition without time pressure – even slightly better for global landmark learning. However, in Study II, the stress condition was specifically designed to impair WM functioning (i.e., using spatial concurrent task load; Labate et al., 2014), the manipulation check indicated increased distress ratings (Matthews et al., 2013), and participants' survey knowledge acquisition was indeed diminished.

These results accord with the critical relationship between WM and survey knowledge acquisition (Hegarty et al., 2006; G. L. Allen et al., 1996) and confirm multiple studies in which dual-task conditions had a negative effect on spatial knowledge acquisition in general (Coluccia et al., 2007; Labate et al., 2014; Gras et al., 2013; Wen et al., 2011, 2013; Meilinger et al., 2008; Labate et al., 2014). The importance of WM functioning as a moderator for survey knowledge acquisition under stress is also supported by the results of the model selection approach presented in Chapter 6. These analyses revealed that participants' distress ratings (SSSQ) were the best predictors of stress-induced impairments in survey knowledge. Indeed, increased distress ratings can be strongly associated with increased WM load (Matthews et al., 2013). In contrast, measures of electrodermal activity were weak predictors for spatial learning performance in the present studies. This might suggest that survey knowledge impairments are less driven by physiological processes and more driven by a multitude of psychological factors that emerge in combination with task demands (Matthews et al., 1999).

Prior research has pointed to the advantage of objects or landmarks that are globally visible for spatial learning (H. Li et al., 2016; Lupo et al., 2018; Lecerf & De Ribaupierre, 2005), but the benefits of such landmarks have not been compared to the benefits of locally visible landmarks during highly demanding tasks such as navigation under time pressure or increased external task load. The present work has demonstrated that contextual stressors may affect survey knowledge acquisition but their effect on learning local landmark configurations was similar to the effect on learning global landmark configurations. Specifically in Study II, this pattern suggests that the spatial component of WM is similarly involved during survey knowledge acquisition for local and global landmark configurations. These results are in conflict with the finding that the encoding of simultaneously visible objects relies more on processing spatial WM resources than the encoding of sequentially visible objects (Lecerf & De Ribaupierre, 2005). The present findings may be better explained by a domain-general impairment of WM due to performing a spatial concurrent task. According to a domain-general interpretation of the results, the spatial concurrent task may have redirected attentional resources away from the knowledge acquisition task (Barrouillet et al., 2011; Kane & Engle, 2003). Hence, the negative effects on mental information processing were independent of the domain of the task (e.g., spatial, visual, or verbal). This explanation is consistent with several studies that demonstrated cognitive interference across domains (e.g., Garden et al., 2002; Vergauwe et al., 2010). To rule out whether the efficient encoding of locally and globally visible landmarks relies on different domain-specific storage pools, future research could extend my research. For example, an extended version of Study II could also include an experimental group that performs a domain-specific, but non-spatial, task (e.g., generating random digits). However, a critical challenge in this approach would be to match the various domain-specific tasks in terms of overall difficulty.

Chapter 8

CONCLUSION

8.1 MAIN FINDINGS

Today, the negative effects of widespread use of navigation assistance on spatial learning raise the issue of which environmental features could be utilized to help navigators acquire spatial knowledge (e.g., Huang et al., 2012). Prior research has shown that landmarks support orientation and the formation of spatial knowledge from the vast amounts of available spatial details that we perceive in the world (Evans et al., 1984; Couclelis et al., 1987; Sadalla et al., 1980; Presson & Montello, 1988; Golledge, 1999; Sorrows & Hirtle, 1999). Towards this end, some evidence from spatial cognition research has pointed to the spatial learning benefits of objects or landmarks that are simultaneously visible in the same vista space compared to objects or landmarks that are sequentially visible in separate vista spaces (Colle & Reid, 1998; Weisberg et al., 2014; Wang & Brockmole, 2003; Ruotolo et al., 2012; Meilinger, Strickrodt, & Bülthoff, 2016). However, virtual reality navigation research on the affects of globally visible landmarks on survey knowledge acquisition of environmental space has produced mixed results (Castelli et al., 2008; H. Li et al., 2016; Meilinger, Schulte-Pelkum, et al., 2015). It is not clear what factors caused these mixed results. To address this research gap, I examined participants' spatial memory performance in an explicit spatial learning task during navigating virtual cities from a first-person perspective. These studies represent the first systematic comparison of spatial learning for multiple local landmarks compared to spatial learning for multiple global landmarks that were either along the route or visible at a distance for a pedestrian navigator in a virtual environment. Furthermore, another aim of this thesis was to elucidate the difficulty of mentally encoding and constructing survey knowledge of local and global landmark configurations in working memory (WM) with and without stressful navigation contexts.

The present thesis provides evidence for a spatial learning advantage of simultaneously visible global landmarks that are located along the route over landmarks that are only locally visible and over landmarks that are globally visible but located at a distance. This suggests that the spatial learning advantage only emerges for globally visible landmarks if the encoding of spatial locations is supported by multiple learning mechanisms such as path integration and route learning. When these learning mechanisms are combined with the allocentric information provided by globally visible landmarks along the route, the present data demonstrates that survey knowledge is acquired more accurately. Further work is needed to precisely understand the cognitive mechanisms that lead to a spatial learning advantage of global landmarks along the route compared to distal global landmarks. For instance, the present results support the notion of Siegel and White (1975) that survey knowledge is based on, or at least supported by, route memory. From a practical perspective, empirical research will be required to find efficient means to automatically select globally visible landmarks along a user's route and guide her attention towards these landmarks without disrupting WM functioning.

The present empirical findings support the relevant role of WM for mentally integrating spatial information into a survey representation during navigation. Specifically, the results of Study II connect findings related to spatial WM across spatial scales and imply a key role for WM capacity for simultaneously visible global landmarks, but not for local landmarks. The lack of finding a relationship between local landmark learning and WM capacity may be explained by a 'floor effect' that resulted from the significant difficulty of the learning task. From this perspective, the present data accords with the expectation that encoding locally visible landmarks should be more difficult than encoding globally visible landmarks using WM, but future research could test this hypothesis by observing local and global landmark learning during multiple learning trials. Furthermore, the use of eye-tracking data collection method would allow to observe perceptual processes that were not observable in the chosen experimental designs for this thesis. For example, eye tracking should help researchers getting insights into how learners allocate attention to local and global landmark information and how such patterns change when landmarks are highlighted on mobile maps. Such studies could for example investigate navigators gaze patterns during local and global landmark learning with and without mobile maps and examine the relationship between landmark fixations and the accuracy of acquired survey knowledge.

The present results suggest that stress-induced impairments of survey knowledge are related to compromised WM. In Study I, time pressure did not significantly affect survey knowledge acquisition, and manipulation check suggested that WM was not impaired due to induced time pressure. When the "stress condition" was designed to impair WM functioning and the manipulation check also indicated increased distress ratings in Study II, participants' survey knowledge acquisition did diminish. This finding is consistent with prior research that has shown impaired spatial learning performance due to concurrent task load (Wen et al., 2011; Gras et al., 2013; Wen et al., 2013; Meilinger et al., 2008). However, the present studies did not show that local and global landmark learning was impaired differently by concurrent task demands. This finding is also inconsistent with the relationship between WM capacity and global landmark learning described earlier. This may suggest that spatial learning with the spatial tapping task was too difficult for participants overall. Future studies should investigate local and global landmark learning under lower levels of cognitive load to investigate this possibility.

Taken together, the present empirical findings have important implications for the development of future navigation systems. My data supports the recommendation to develop systems that guide attention towards global landmarks along the route and thereby reduce the difficulty associated with encoding the locations of landmarks. Such systems should efficiently support survey knowledge acquisition with respect to a user's cognitive load. Importantly, the ability to utilize such systems for the support of survey knowledge acquisition should not be generalized to everyone but may depend on individual differences in WM capacity and might not be useful in all situations (e.g., when distracted by tasks that require attention).

8.2 DESIGN RECOMMENDATIONS

Based on the present empirical evidence, this section provides design recommendations for *learning-aware navigation systems*. Here, this term is used to describe digital assistive systems that aim to provide information that is relevant for wayfinding and to support users in spatial learning during navigation. The recommendations refer specifically to improving the acquisition of survey knowledge in long-term memory and are effective only if participants actively attend to particular landmarks in the environment. One major contribution of the present thesis is to elucidate the characteristics of these landmarks that facilitate survey knowledge acquisition and thus should be highlighted in learning-aware navigation systems for pedestrians. Ultimately, my results can be utilized to inform the design of map-based (or any other) navigation systems (e.g., acoustic, verbal, etc.) by providing insights into which aspects of the environment the system should guide a pedestrian's attention to foster mental encoding. When compared to map learning, the acquisition of survey knowledge from attending spatial relations directly in the environment might require participants to spend more time initially for the learning task but should lead to more accurate route and survey representations over a long period of time (Thorndyke & Hayes-Roth, 1982). With advances in augmented reality technology (e.g., Google Maps AR navigation, smart glasses and lenses, etc.), future navigation systems will have more efficient means to guide the attention of their users to environmental aspects without negative effects of dividing attention between navigation device and environment (Gardony et al., 2013).

8.2.1 Global visibility

What properties of landmarks facilitate efficient survey knowledge acquisition? The present findings show that landmarks should be globally visible and located along the route that one is traveling. Together, these characteristics allow navigators to stay oriented with respect to the traveled route, to attend these landmarks simultaneously, and to use them as intermediate goal locations to support memory acquisition. Due to their location along the route, navigators are able to encode their locations using route learning and path integration.

> The learning support provided by navigation systems should direct attention towards a small selection of globally visible landmarks that are located along the route to increase the efficiency of survey knowledge acquisition.

Typically, modern wayfinding instructions are based on computing optimal routes to a destination (Raubal & Winter, 2002). The present findings imply that to enhance survey knowledge acquisition during navigation, learning-aware navigation devices should highlight the most globally visible landmarks along that route to a navigator. If no globally visible landmarks are available along a given route, the system could turn local landmarks to globally visible structures and enable users to mentally integrate these structures in a survey representation. In this way, future systems could flexibly highlight known landmarks for orientation and unfamiliar landmarks to initiate spatial learning. In any case, the landmark selection process should also be optimized with respect to visual, structural, and semantic salience metrics (e.g., Röser, 2015).

8.2.2 Use context

In what situations is it actually useful to guide a user's attention to global landmarks for the support of survey knowledge acquisition? In accordance with prior research, the present findings demonstrate that users allocate attentional resources from WM to learn environmental spaces (Wen et al., 2011; Meilinger et al., 2008; Gras et al., 2013). However, guiding a navigator's attention to a learning task might not always be desirable. When people perform other tasks in addition to navigation and wayfinding, WM resources are limited, and users need to divide attentional resources among the different tasks (Gardony et al., 2013). For example, when driving a car, one's attention is typically required for safely operating the car and adhering to traffic rules, increasing the task load by displaying additional features may cause a security risk. Similarly, in the domain of pedestrian navigation, we can imagine situations in which additional workload is not desirable. Indeed, people often navigate while performing several other tasks (e.g., talking to a travel companion, using the phone) which draw on the same attentional resources. The present study has shown that users' survey knowledge acquisition is impaired in such situations. Complementary to this, the efficient performance on the concurrent task is also impaired when people expend mental effort on learning.

> To increase the efficiency of survey knowledge acquisition, the display of unfamiliar global landmarks should appear primarily when the user's cognitive resources are not needed for other tasks.

Future navigation devices should respond in real-time to concurrent task load and adapt the display of learning features accordingly. To do so, such systems need to find means to assess concurrent task load using mobile technology. For example, reasonable approaches to sense a participant's concurrent task load online could be to measure interaction frequency, walking speed, and voice activity.

8.2.3 Spatial abilities

Which users should be made aware of global landmarks? The present data demonstrate that learning the spatial configuration of environments is a fundamentally difficult and a cognitively demanding task. Users with low spatial WM capacity generally demonstrated weak spatial learning performance. They were not able to take advantage of the visibility of global landmarks. With increased WM capacity, users showed improved survey knowledge acquisition when global landmarks along the route were highlighted in the environment. Spatial WM capacity can be tested using complex span tasks such as the Symmetry Span Test (Kane et al., 2004) that requires only 5 to 10 minutes.

> To increase the efficiency of survey knowledge acquisition, systems should guide attention towards unfamiliar global landmarks only if participants have at least moderate scores on WM capacity tests.

Future navigation systems should query the WM capacity of their users and adapt the spatial memory training accordingly. In addition, such systems should remain updated regarding changes to participants' spatial strategies and abilities to adapt the display or initiate training when necessary. However, testing participants cognitive capabilities may have some unwanted side effects. For example users may not be willing to share personal data, like the score of a spatial ability test, with their navigation system provider. Furthermore, users who know that the automatic display of certain features is related to their spatial ability score may feel discouraged when display of these features does not appear. One way of tackling this issue could be to provide users with the WM capacity test results and recommendations about the landmark display, but to still leave the option of displaying landmarks to the user. Future research may want to investigate the psychological side effects of pedestrian navigation devices that query WM capacity and automatically adapt the information display.

8.3 OUTLOOK

The present thesis has empirically established, for the first time, conditions that help to classify globally visible landmarks according to their utility for spatial learning. However, there are still many open questions regarding the mental encoding of landmark configurations and how global visibility may support survey knowledge acquisition. Future research should further investigate the properties of landmarks that may improve their integration into survey representations during navigation.

This thesis points to further open questions regarding the characteristics of globally visible landmarks that enhance survey knowledge acquisition during pedestrian navigation. For example, differences in the present data between navigators' spatial memory accuracy of globally visible landmarks that were located along the route and those that were visible at a distance may indicate a relevant role of their spatial arrangement. Previous evidence has shown that the arrangement of objects might play a critical role for the formation and recall of spatial memory in figural space (Shelton & McNamara, 2001; Burgess et al., 2004; Mou & McNamara, 2002). However, considerably less is known regarding the role of salient landmark arrangements when people develop survey knowledge during navigation through large environmental spaces (e.g., Werner & Schmidt, 1999; Kelly & McNamara, 2010). It is possible that global landmarks along the route may support spatial learning more strongly if they are located at specific intersections or in specific distances from each other. For example, the walking distance between two local landmarks might affect survey knowledge acquisition more than the walking distance between two global landmarks along the route. Similarly, if landmarks shape a salient axis or a symmetrical layout from a bird's eye perspective they might support survey knowledge acquisition from first-person perspective (e.g., Appleyard, 1970; Lynch, 1960). The investigation of such research topics should help to further inform the selection and display of salient landmark configurations in learning-aware navigation systems. Based on the insights of such basic research, application-oriented research could be conducted to investigate the technical implementations of pedestrian navigation systems to make such aspects globally visible to their users.

Regarding the importance of spatial abilities for survey knowledge acquisition, further empirical studies are needed to shed light on which kind of spatial information is helpful for users with low spatial abilities, and whether or when these users are able to exploit the learning advantage of global landmarks. Whilst this thesis did confirm a moderating role of spatial WM capacity for spatial learning of global landmarks, it still remains unclear how other kinds of spatial abilities (e.g., mental rotation, perspective taking) are related to processing different landmark types. Additionally, different spatial orientation strategies might influence the utility of highlighting global landmarks along the route for survey knowledge acquisition. I could not find a relationship between spatial orientation strategies and the acquisition of survey knowledge when participants learned local landmarks or global landmarks seen at a distance. Future studies could examine the relationship between global landmarks along the route and individual differences in orientation strategies. A reasonable approach to tackle the role of orientation strategies with respect to spatial learning performance of local and global landmarks might be to assess and compare the explanatory power of different self-reported strategic aspects (Münzer & Hölscher, 2011; Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002).

To test if effects of stress on spatial memory (Richardson et al., 1999; Duncko et al., 2007) are more driven by physiological processes or more driven by a multitude of psychological factors that emerge in combination with task demands (Matthews et al., 1999), future research should modify the severity of a stressor (Kirschbaum et al., 1993). Aside from assessing EDA, this research could collect participants' glucocorticoid levels which might serve another physiological indicator of participants' stress states (e.g., Thoresen et al., 2016; Elzinga & Roelofs, 2005). Glucocorticoids are exerted by the hypothalamic-pituitary-adrenal axis and can be considered physiological markers of stress that impair WM functioning (Oei et al., 2006). Such an alternate approach might be a further step to understand the role of compromised WM in the relationship between stress and survey knowledge acquisition.

Future research with VR should consider the possible influences of bodily cues (e.g., linear and angular accelerations) during natural self-motion on spatial knowledge acquisition. For example, bodily cues may facilitate learning landmarks along the route more than learning distal landmarks. I have discussed the potential implications of a lack of bodily cues during VR navigation in Section 4.4. To further address these concerns, future research may also want to employ VR systems that provide participants with naturalistic multi-sensory self-motion cues. However, VR systems that provide naturalistic self-motion cues impose significant practical challenges with respect to navigation and spatial knowledge acquisition of large-scale virtual environments. For example, in the technique called "redirected walking", physical rotations and movements are transformed into increased or decreased rotations and movements in the virtual environment (i.e., gain). Using this technique allows users of VR systems to navigate large-scale virtual environment while physically moving in a small-scale open space. However, the technique has limitations with respect to high levels of gain. For instance, with increasing manipulations of gain, redirected walking may increase the cognitive load on verbal and spatial WM of participants and thus affect spatial learning (Bruder, Lubos, & Steinicke, 2015).

Furthermore, future navigation research in VR will need to continue seeking ways to reduce simulator sickness. I have discussed the challenges with simulator sickness and spatial knowledge acquisition during VR navigation in Section 7.2. To address this issue, future research with VR should rely on careful manipulation checks (e.g., pre- and post-task sickness questionnaires) as employed for the present thesis. Researchers may also provide participants with extensive VR habituation before the experiment. One way of reducing the amount of time required by participants for VR habituation could be to provide multi-sensory simulations. This approach might help increase participants' sense of "presence" in the virtual environment (Cummings & Bailenson, 2016).

Finally, VR technologies enable researchers from different fields to create environments with nearly unlimited architectural freedom. In this respect, some evidence supports the implementation of more realistic visual representations (e.g., high fidelity textures, geometrical details, shadows, image quality) for engaging users and improving their spatial memory for VR environments (e.g., Wallet et al., 2011; Meijer, Geudeke, & Van den Broek, 2009). Accordingly, the present thesis employed virtual environments with photorealistic textures and the typical architectural details of cities (e.g., house facades, zebra crossings, sidewalks, trees). In addition, participants experienced a virtual train ride before every city navigation trial in order to increase the believability of the navigation scenario and thus improve the participants' sense of presence (Freeman, Lessiter, Pugh, & Keogh, 2005b). With VR, I could also selectively exclude details that were unnecessary or undesirable (e.g., slope, weather, traffic) and would have prevented a clear view of the variables of interest in a similar real world experiment.

In general, my findings support the utility of realistic virtual environments as a research tool for investigating cognitive processes during navigation and spatial knowledge acquisition. In both of the present studies, participants were able to acquire survey knowledge during navigation through a virtual large-scale environment with primarily visual feedback. Even in experimental conditions that resulted in the weakest JRD performance, participants' accuracy was better than chance. These insights about the accuracy of survey knowledge acquired during VR navigation add to the growing literature that supports the general utility of VR for studying spatial memory (Ruginski, Stefanucci, & Creem-Regehr, 2018; Richardson et al., 1999; Foreman et al., 2000; Bliss et al., 1997; Gillner & Mallot, 1998; Warren et al., 2017; Schnapp & Warren, 2007, e.g.,).

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Chapter A

APPENDIX

A.1 QUESTIONNAIRES

In den folgenden Fragen geht es um deine **momentanen Gefühle und Gedanken**. Bitte beantworte jede Frage, auch wenn es schwierig ist. Gebe so ehrlich wie möglich an, was auf dich zutrifft. Wähle keine Antwort, nur weil sie wünschenswert scheint. Deine Antwort wird vertraulich behandelt. Beachte auch, deine Antworten nur danach zu wählen, wie du dich **IN DIESEM MOMENT** fühlst. Gebe nicht einfach an, wie du dich gewöhnlich fühlst. Versuche möglichst schnell zu sein: Es gibt keinen Grund über die Antworten lange nachzudenken. Die erste Antwort, die dir einfällt, ist gewöhnlich die beste.

Markiere für jede Aussage eine Antwort zwischen 0 und 4, die deine Gefühle und Gedanken IM MOMENT am besten beschreibt:

0 = Trifft im Moment überhaupt nicht zu
1 = Trifft im Moment eher nicht zu
2 = Momentan weder unzutreffend noch zutreffend
3 = Trifft im Moment eher zu
4 = Trifft im Moment völlig zu

	0	1	2	3	4
1. Ich sorge mich um den Eindruck, den ich mache.					
2. Ich fühle mich entspannt.					
3.Der Inhalt der Aufgabe wird langweilig sein.					
4. Ich denke darüber nach, wie andere meine Leistung beurteilen könnten.					
5. Ich bin entschlossen, die Aufgabe erfolgreich zu bewältigen.					
6. Ich fühle mich angespannt.					
7. Ich mache mir Sorgen darüber, was andere von mir denken.					
8. Ich denke darüber nach, wie ich mich fühlen würde, wenn ich gesagt bekäme, wie meine Leistung in der Aufgabe ist.					
9. Im Allgemeinen habe ich das Gefühl, Herr der Lage zu sein.					
10. Ich sinne über mich selbst nach.					
11. Meine Aufmerksamkeit wird auf die Aufgabe gerichtet sein.					
12. Ich wälze Gedanken über mich selbst.					
13. Ich fühle mich energiegeladen.					
14. Ich denke über Dinge nach, die mir in der Vergangenheit passierten.					
15. Ich denke darüber nach, wie andere diese Aufgabe bewältigen würden.					
	0	1	2	3	4
16. Ich denke an etwas, das heute passiert ist.					
17. Ich erwarte, dass die Aufgabe zu schwierig für mich sein wird.					
18. Es wird mir schwer fallen, meine Konzentration bei der Aufgabe zu halten.					
19. Ich denke über persönliche Angelegenheiten und Belange nach.					
20. Ich fühle mich zuversichtlich hinsichtlich meiner Leistung in der Aufgabe.					
21. Ich prüfe meine Beweggründe.					
22. Ich kann mit allen Schwierigkeiten umgehen, die mir begegnen können.					
23. Ich denke daran, wie ich ähnliche Aufgaben in der Vergangenheit erledigte.					
24. Ich reflektiere über meine Gründe, die Aufgabe zu machen.					
25. Ich bin motiviert, mich bei der Aufgabe anzustrengen.					
26. Ich denke über Dinge nach, die mir wichtig sind.					
27. Ich fühle mich unbehaglich.					
28. Ich fühle mich müde.					
29. Ich habe das Gefühl, die Situation nicht erfolgreich bewältigen zu können.					
30. Ich fühle mich gelangweilt.					

Figure 34: Pre-task Short Stress State Questionnaire (SSSQ; Helton, 2004).

In den folgenden Fragen geht es um deine Gefühle und Gedanken während der letzten Navigationsaufgabe. Bitte beantworte jede Frage, auch wenn es schwierig ist. Gebe so ehrlich wie möglich an, was auf dich zutrifft. Wähle keine Antwort, nur weil sie wünschenswert scheint. Deine Antwort wird vertraulich behandelt. Beachte bitte, deine Antworten nur danach zu wählen, wie du dich **WÄHREND DER LETZTEN MINUTE DER ZWEITEN NAVIGATIONSAUFGABE** gefühlt hast. Gebe <u>nicht</u> einfach an, wie du dich gewöhnlich fühlst. Versuche möglichst schnell zu sein: Es gibt keinen Grund über die Antworten lange nachzudenken. Die erste Antwort, die dir einfällt, ist gewöhnlich die beste.

Wie waren deine Gefühle und Gedanken WÄHREND DER LETZTEN MINUTE DER ZWEITEN NAVIGATIONSAUFGABE?

0 = Trifft in der letzten Minute der Aufgabe überhaupt nicht zu
1 = Trifft in der letzten Minute der Aufgabe eher nicht zu
2 = In der letzten Minute der Aufgabe weder unzutreffend noch zutreffend
3 = Trifft in der letzten Minute der Aufgabe eher zu
4 = Trifft in der letzten Minute der Aufgabe völlig zu

	0	1	2	3	4
1. Ich sorgte mich um den Eindruck, den ich mache.					
2. Ich fühlte mich entspannt.					
3. Der Inhalt der Aufgabe war langweilig.					
4. Ich dachte darüber nach, wie andere meine Leistung beurteilen könnten.					
5. Ich war entschlossen, die Aufgabe erfolgreich zu bewältigen.					
6. Ich fühlte mich angespannt.					
7. Ich machte mir Sorgen darüber, was andere von mir denken.					
8. Ich dachte darüber nach, wie ich mich fühlen würde, wenn ich gesagt bekäme, wie meine Leistung in der Aufgabe ist.					
9. Im Allgemeinen hatte ich das Gefühl, Herr der Lage zu sein.					
10. Ich sinnte über mich selbst nach.					
11. Meine Aufmerksamkeit war auf die Aufgabe gerichtet.					
12. Ich wälzte Gedanken über mich selbst.					
13. Ich fühlte mich energiegeladen.					
14. Ich dachte über Dinge nach, die mir in der Vergangenheit passierten.					
15. Ich dachte darüber nach, wie andere diese Aufgabe bewältigen würden.					
	0	1	2	3	4
16. Ich dachte an etwas, das heute passiert ist.					
17. Ich fand, dass die Aufgabe zu schwierig für mich ist.					
18. Es fiel mir schwer, meine Konzentration bei der Aufgabe zu halten.					
19. Ich dachte über persönliche Angelegenheiten und Belange nach.					
20. Ich fühlte mich zuversichtlich hinsichtlich meiner Leistung in der Aufgabe.					
21. Ich prüfte meine Beweggründe.					
22. Ich konnte mit allen Schwierigkeiten umgehen, die mir begegneten.					
23. Ich dachte daran, wie ich ähnliche Aufgaben in der Vergangenheit erledigte.					
24. Ich reflektierte über meine Gründe, die Aufgabe zu machen.					
25. Ich war motiviert, mich bei der Aufgabe anzustrengen.					
26. Ich dachte über Dinge nach, die mir wichtig sind.					
27. Ich fühlte mich unbehaglich.					
28. Ich fühlte mich müde.					
29. Ich hatte das Gefühl, die Situation nicht erfolgreich bewältigen zu können.					
30. Ich fühlte mich gelangweilt.					

Figure 35: Post-task Short Stress State Questionnaire (SSSQ; Helton, 2004).

Bitte kreuze an, wie sehr die folgenden Symptome auf deinen momentanen Zustand zutreffen

	gar nicht	etwas	mittel	stark
Allgemeines Unwohlsein				
Ermüdung				
angestrengte Augen				
erhöhter Speichelfluss				
Schwierigkeiten scharf zu sehen				
Übelkeit				
Konzentrationsschwierigkeiten				
Kopfdruck				
verschwommenes Sehen				
Schwindel (Augen offen)				
Schwindel (Augen geschlossen)				
Aufstossen				
Schwitzen				
Magen macht sich bemerkbar				
Kopfschmerzen				
Gleichgewichtsstörungen				

Figure 36: Simulator Sickness Questionnaire (SSQ; Kennedy, Lane, Berbaum, & Lilienthal, 1993)

Fragebogen Räumliche Orientierung

Dieser Fragebogen enthält Aussagen zu Verhaltensweisen beim Zurechtfinden in räumlichen Umgebungen. Wir bitten Sie, für *jede* Aussage anzuzeigen, inwieweit Sie der Aussage zustimmen. Die Möglichkeit zur Ablehnung bzw. Zustimmung hat die folgende Form:

lehne stark ab 1 2 3 4 5 6 7 stimme stark zu

Bitte markieren Sie für jede Aussage diejenige Position, die dem Grad Ihrer Zustimmung am besten entspricht.

		lehne stark ab						stimme stark zu
1	Wenn ich durch eine unbekannte Stadt laufe, dann weiß ich, aus welcher Richtung ich gekommen bin und in welche Richtung ich mich bewege.	1	2	3	4	5	6	7
2	Wenn mich jemand in meiner Stadt nach dem Weg fragt, dann stelle ich mir meine Stadt wie auf einer Karte vor und ermittle daraus den Weg.	1	2	3	4	5	6	7
3	Wenn ich mich durch ein großes Gebäude bewege, dann stelle ich mir dabei eine Art Plan oder Grundriss (Überblicksansicht) vor.	1	2	3	4	5	6	7
4	Ich bin sehr gut darin, von meinem gegenwärtigen Standort aus Richtungen zu anderen Orten anzugeben.	1	2	3	4	5	6	7
5	In der freien Natur (z.B. Wald, Gebirge) kann ich mich an einen Weg sehr gut erinnern, wenn ich ihn einmal gegangen bin.	1	2	3	4	5	6	7
6	Ich kann spontan zeigen, wo Norden, Süden, Osten und Westen liegt.	1	2	3	4	5	6	7
7	Ich stelle mir die Umgebung stets wie auf einer „mentalen Karte“ (Überblicksansicht) vor.	1	2	3	4	5	6	7
8	Ich finde stets ohne Probleme zu meinem Ziel.	1	2	3	4	5	6	7
9	In der freien Natur versuche ich, die räumlichen Gegebenheiten aus der Vogelperspektive zu verstehen.	1	2	3	4	5	6	7
10	In einer unbekannten Umgebung finde ich mich gut zurecht.	1	2	3	4	5	6	7
11	Wenn ich in meiner Stadt unterwegs bin, dann kann ich mir meine Position wie einen Punkt auf meiner „mentalen Karte“ vorstellen.	1	2	3	4	5	6	7
12	Ich bin sehr gut darin, mir Wege zu merken und finde auch ohne Mühe den Rückweg.	1	2	3	4	5	6	7
13	In einem großen Gebäude habe ich keine Schwierigkeiten, einen Weg nochmals zu gehen, wenn ich den Weg einmal gegangen bin.	1	2	3	4	5	6	7
14	Mein Orientierungssinn ist sehr gut.	1	2	3	4	5	6	7
15	In meiner Stadt kann ich von einem beliebigen Punkt aus spontan angeben, in welchen Richtungen markante Gebäude oder Bezugspunkte liegen.	1	2	3	4	5	6	7
16	Ich verfüge über eine sehr gute Vorstellung von meiner Stadt, wie auf einer Karte.	1	2	3	4	5	6	7
17	In der freien Natur kann ich spontan zeigen, wo Norden, Süden, Osten und Westen liegt.	1	2	3	4	5	6	7
18	In einem großen Gebäude weiß ich spontan, in welcher Richtung der Eingang liegt.	1	2	3	4	5	6	7
19	Wenn ich mich in einer unbekannten Stadt bewege, dann bilde ich in meiner Vorstellung eine Art „mentale Karte“.	1	2	3	4	5	6	7

O männlich O weiblich Alter:

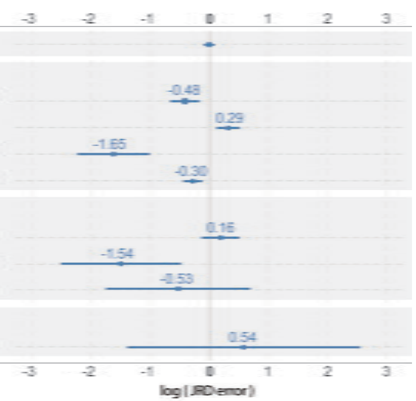
Studienfach:

Figure 37: Fragebogen Räumliche Strategien (FRS; Münzer and Hölscher, 2011)

A.2 SUPPLEMENTARY MATERIAL

Variable Name	Study I (N = 43)	Study II (N = 48)
EDA: NS-SCR/min		
min	-0.61	-0.88
max	0.35	0.32
mean (sd)	-0.02 ± 0.20	-0.12 ± 0.22
EDA: Tonic SCL		
min	-1.39	-3.19
max	7.61	6.20
mean (sd)	1.74 ± 1.61	2.62 ± 1.73
SSSQ: distress		
min	-1.57	-2.04
max	3.42	2.88
mean (sd)	0.51 ± 0.94	0.58 ± 0.81
SSSQ: engagement		
min	-2.41	-1.80
max	2.66	2.70
mean (sd)	0.14 ± 1.04	0.37 ± 0.95
SSSQ: worry		
min	-2.86	-2.87
max	0.38	0.30
mean (sd)	-0.68 ± 0.73	-0.72 ± 0.70
Simulator Sickness		
min	-0.68	-26.18
max	3.55	97.24
mean (sd)	0.61 ± 0.90	11.45 ± 26.37

	β	Std. Error	df	t value	p	95% CIs
Intercept	3.53	0.06	30.1	63.78	< .0001	(3.42 , 3.64)
Main Effects						
LM (global) ***	-0.48	0.10	21.58	5.07	< .0001	(-0.67 , -0.29)
TAP (with) **	0.29	0.10	47.59	2.95	.0049	(0.10 , 0.49)
WM span (high) ***	-1.65	0.31	47.81	-5.34	< .0001	(-2.25 , -1.04)
trial_number (2) ***	-0.30	0.08	46.74	3.57	.0005	(-0.46 , -0.14)
Two-Way Interactions						
LM x TAP	0.16	0.16	46.16	0.71	.3238	(-0.16 , 0.48)
LM x WM span **	-1.54	0.51	46.02	2.38	.0044	(-2.54 , -0.53)
TAP x WM span	-0.53	0.61	46.96	0.57	.3884	(-1.73 , 0.67)
Three-Way Interaction						
LM x TAP x WM span	0.54	0.99	45.43	0.54	.5862	(-1.40 , 2.49)



LM = Landmark Type; TAP = Spatial Tapping; WM = Working Memory; CIs = Confidence Intervals

*** p < .001; ** p < .01; * p < .05

Figure 38: A list of the fixed effects regression coefficients based on the log-transformed data. The intercept is the grand mean, and other coefficients are estimated differences between a group mean and the grand mean. Confidence intervals were computed using the Wald test. As in the untransformed data, there were significant main effects of landmark type, tapping group, WM span, and trial number.

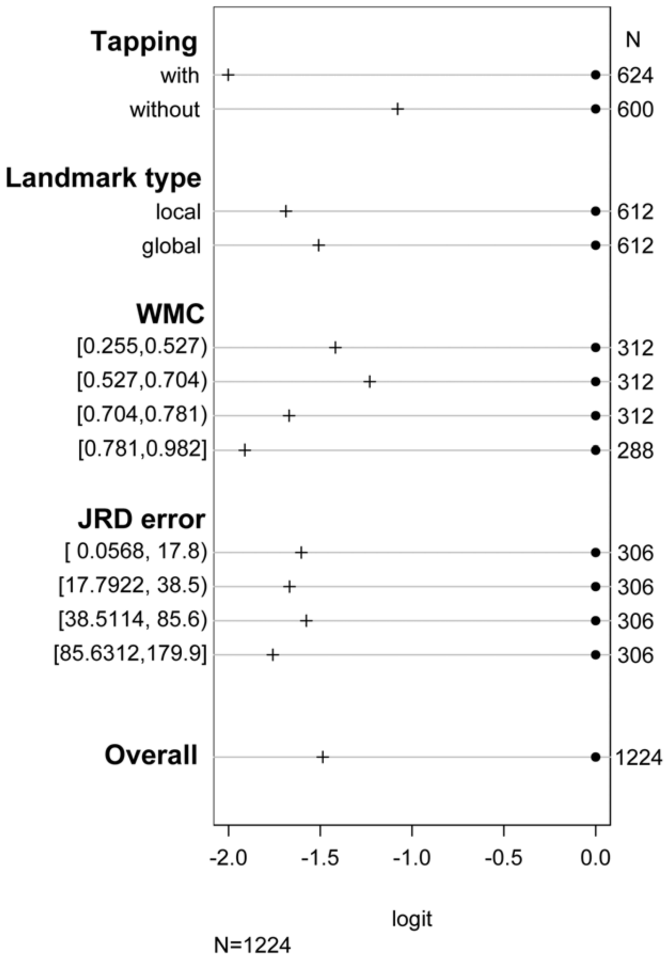


Figure 39: The values displayed in this graph are linear predictions from a logit model that estimate the probability that the response variable is greater than or equal to a given value (for each level of the predictor variable), using one predictor variable at a time. If the horizontal distances between the estimations within each predictor remain similar, then we can assume parallel slopes and the proportional odds assumption holds. The graph that is proposed by Harrell J (2015) displays the model predictions against zero, so there is a common reference value. Generally, the results indicate that all predictors hold with the proportional odds assumption, only for the tapping condition, results should be interpreted with caution.

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